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Residential water and energy use linkages: Integrating data and policy

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Abstract

Integrated water and energy management presents a significant opportunity to address the growing resource intensity of cities, by taking advantage of synergies between water and energy efficiency approaches, and by avoiding unintended consequences of ‘problem shifting’ between the water and energy spheres. Residential end use of water has been estimated to account for energy use between 4.7 and 11.2 times that associated with the delivery of urban water services in Australia. Consequently, there is wide potential for energy management in the urban water cycle within households.

This thesis aims to highlight policy opportunities for integrated management of residential water and energy use in urban Victoria. This is achieved through a focus on three specific research objectives, as follows:

Research objective 1: Understanding variation in water-related energy (WRE) use between households

> *WRE use ranged from 7 to 21 kWh per household per day, with variation between households driven primarily by shower use (11 – 61% WRE), hot water system efficiency losses (8% - 31% WRE) and clothes washer usage (4 - 17% WRE).*

The approach involved detailed quantification of WRE use in seven highly-monitored individual households, and identification of household characteristics which contributed most significantly to variation in WRE between households. Empirical data were collected to characterise 139 parameters describing household occupancy characteristics, behaviours, technologies, and structural and environmental aspects of influence for water and energy use. Mathematical flow analysis modelling (MMFA) was conducted for individual water and energy use sub-systems in each household. Findings highlighted shower use as a consistent influence on WRE use across households, suggesting further investigation of shower programs as a potentially effective demand management measure for both water and energy in households. The work also highlighted the importance of consistent messaging for both water and energy efficiency.

Research objective 2: Gauging the effect of household water demand management on WRE use

> *A shift to four-minute showers in the households studied would reduce WRE use to between 30% and over 1000% of the average energy required for water service provision to the same households.*

This research explored the range of potential energy use impacts of shower water demand management through a case study of households characterised for Objective 1, and assessed the differences in energy and cost responses for four different hot water system types. Analysis was conducted through modelling of a hypothetical four-minute shower scenario (from current durations of between six and ten minutes) using the MMFA models developed through Objective 1. Results showed that the demand management scenario would lead to a reduction of between 0.1 and 3.8 kWh p^{-1} d^{-1} in the households studied, comprising 9% to 64% of baseline hot water system energy use. Contrasted with an average energy use for water service provision in Melbourne of 0.3 kWh p^{-1} d^{-1}, such household reductions demonstrate significant potential for urban water cycle energy management.

Objective 3: Exploring the potential for policy and regulation for household WRE management in urban Victoria

> *Cost of living issues offer a common basis for cross-sectoral stakeholders to underpin integrated water-energy management policy. Key policy opportunities include consumer education and advocacy, and further development of residential building standards. Changes in state government policy and priorities may offer the best context for policy change.*

The approach for this research objective drew on the fields of transitions management and institutional entrepreneurship. To understand how to facilitate a transition towards policy for improved WRE management, enabling conditions for institutional entrepreneurship (or policy innovation) by key actors were identified. Semi-structured interviews were conducted with 17 stakeholders with an interest in the management of household water or energy use in urban Victoria. Analysis of interview transcripts focused on three themes: (a) objectives and mechanisms for influencing household WRE use; (b) past experiences of successful policy innovation; and (c) perspectives on improved household WRE management. Key findings suggested that to create an enabling environment for policy innovation for improved household water-related energy management, a focus on the following may be beneficial: (i) policy framing focused on impacts of WRE use on household cost of living; (ii) advocacy to shift state government policy priorities to a clearer WRE focus, or anticipation of emerging priorities and demonstration of corresponding relevance of WRE management; and (iii) collection of data to support cost-benefit analysis. Key policy opportunities identified included consumer education and advocacy for behaviour change and technology choice, and further development of residential building standards to influence the selection and layout of building services at the design phase.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications included in this thesis

1. **Binks, A. N.**, S. J. Kenway and P. A. Lant (2017). "The effect of water demand management in showers on household energy use." Journal of Cleaner Production **157**: 177-189.

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2. Kenway, S. J., **A. Binks**, J. Lane, P. A. Lant, K. L. Lam and A. Simms (2015). "A systemic framework and analysis of urban water energy." Environmental Modelling and Software 73: 272-285.

Conference abstracts

3. **Binks, A. N.,** S. Kenway, B. Head and P. Lant (2016). Energy cost savings for households and utilities via water demand management - new options for efficient cities. World Water Congress 2016. International Water Association. Brisbane, Australia.

4. **Binks, A.**, S. Kenway, P. Lant and F. Pamminger (2014). Detailed characterisation of water-related energy use in households. Ozwater 2014. Australian Water Association. Brisbane.

5. Kenway, S. J., **A. Binks**, J. Bors, F. Pamminger, B. Head, P. Lant, T. Taimre, R. Scheidegger and H.-P. Bader (2015). Quantifying water-energy linkages opens new pathways for efficiency. Ozwater 2016. Australian Water Association. Brisbane, Australia.

6. Kenway, S. J., **A. Binks**, R. Scheidegger, F. Pamminger, P. Lant, T. A. Larsen and H. P. Bader (2014). Analysis of Water-Related Energy in Australian Households Identifies Efficiency Opportunities. World Water Congress 2014. International Water Association. Lisbon, Portugal.

Contributions by others to the thesis

The contributions of co-authors to jointly authored papers included as Chapters 0 and 0 of this thesis are detailed in the statements immediately preceding each chapter.

No contributions were made by others to the remainder of this thesis as a whole.

Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis.

Research Involving Human or Animal Subjects

Ethical review and approval for research involving human subjects undertaken as part of this thesis was obtained, with details as follows:

- Approval number 2012001201, granted 01/11/2012 by the Behavioural and Social Sciences Ethical Review Committee (see Appendix A)
- Approval number 2017000659, granted 20/05/2017 by the Universtiy of Queensland Engineering, Architecture and Information Technology, Low & Negligible Risk Ethics Sub-Committee (see Appendix B).

Copies of the ethics approval letters for each of the above are included as Appendix A and Appendix B of this thesis.

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Water management, energy management, residential, urban, transitions management, institutional entrepreneurship.

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List of Abbreviations

CAPEX	capital expenditure
d	day
GHG	greenhouse gas
GJ	Gigajoule(s)
hh	household(s)
HH	a specific, studied household (e.g., HH1)
HWS	hot water system
kg	kilogram(s)
kg CO2-e	kilograms of carbon dioxide equivalent
kg CO2-e kWh^{-1}	kilograms of carbon dioxide equivalent per kilowatt hour
kWh	kilowatt hour(s) (3.6 megajoules (MJ))
kWh hh^{-1} d^{-1}	kilowatt hour(s) per household per day
kWh hh^{-1} y^{-1}	kilowatt hour(s) per household per year
kWh p^{-1} d^{-1}	kilowatt hour(s) per person per day
L	Litre(s)
L hh^{-1} d^{-1}	Litres per household per day
L hh^{-1} y^{-1}	Litres per household per year
L min^{-1}	Litres per minute
L p^{-1} d^{-1}	Litres per person per day
min	minute(s)
MMFA	mathematical material flow analysis
OPEX	operational expenditure
p	person(s)
p hh^{-1} d^{-1}	persons per household per day
ResWE	the Residential Water-Energy model (refer to Kenway et al. 2013)
WRE	water-related energy

1. **Introduction**

"…We have reached a critical point in understanding that cities can be the source of solutions to, rather than the cause of, the challenges that our world is facing today."

- New Urban Agenda (United Nations 2017), Foreword

Urbanisation presents one of the world's most transformative trends (United Nations 2017). By 2050, the world population is expected to nearly double, and most of this growth will occur in cities. This presents many challenges, not least for the provision of basic services and for our corresponding reliance on limited natural resources. If our urban services are not efficiently designed and delivered, cities run the risk of 'locking in' increasing resource intensity as population growth and urbanisation accelerate. Climate change will compound these challenges through impacts such as resource scarcity, further compromising the adaptive capacity of our cities.

Cities also present opportunities for sustainability. They constitute the intersection where the forces which perpetuate and intensify growth (such as population, consumption, infrastructure and social needs) are clustered (Artioli et al. 2017). Recognition of the importance of the urban setting in the sustainability agenda is best exemplified in the 2016 Sustainable Development Goals, which include a strong focus on urban resilience and sustainability (UNDP 2016). This focus is further highlighted in the New Urban Agenda, the multi-lateral vision for a sustainable future articulated by the secretariat of the United Nations Habitat III conference. The Agenda notes that "if well-planned and well-managed, urbanization can be a powerful tool for sustainable development for both developing and developed countries" (United Nations 2017). Our future cities offer clear potential as thriving, sustainable hubs - but efficient design and management of urban resources is a pressing challenge that must be met if we are to realise this potential.

The urban water sector, both in Australia and internationally, has focused much attention on increasing the resource efficiency of its services. Network pressure and leakage management, combined with consumer education, rebate programs and product regulation have significantly lowered per-capita water consumption rates. Similarly, new and emerging solutions such as waste-to-energy technologies and micro-hydro energy generation, in conjunction with enhanced efforts to optimise system operations, have contributed to managing the energy intensity of our water supplies. While such efforts endure and new solutions will continue to emerge, further efficiency gains are likely to diminish in impact as the lower-hanging fruit have been addressed. The water sector also faces emerging resource management challenges. Growing uncertainty due to climate change necessitates adoption of alternative, often energy-intensive ‘climate-resilient’ water supply options, with the increasing cost of energy supply compounding such pressures (Cook et al. 2012). Going forward, it will be important for the water sector to seek novel approaches to make further gains in the efficient management of resource use in the urban water cycle.

Integrated management of the end use of water and energy may offer significant advantages that have not yet been embraced. The energy use associated with urban water end use (water-related energy use, WRE) is estimated to be as much as 11 times that for water service delivery in Australia (Kenway et al. 2008), half of which occurs in households. Despite the significant potential for efficiency gains, household water-related energy use has not yet been a direct focus of management. Management of energy use through the management of water use may offer substantial efficiency opportunities to limit the resource intensity of our urban environments by maximising synergies between water and energy management, and to avoid perverse consequences through problem-shifting between the water and energy spheres. Households afford particular opportunities for management, as a relatively homogenous set of water-energy end uses for management and as a context of relevance to a broad cross-section of urban society.

This thesis explores the potential for household water-related energy management, with a focus on urban Victoria. The approach taken specifically aims to bridge the fields of engineering and social science, to define practical policy opportunities which may be leveraged in the short to medium term by actors within the existing management landscape. This is achieved through a focus on three research objectives, which are:

1) Understanding variation in water-related energy (WRE) use between households
2) Gauging the effect of household water demand management on WRE use
3) Exploring the potential for policy and regulation for household WRE management in urban Victoria.

1.1. Thesis outline

This thesis comprises eight chapters. Chapter 1 provides an introduction to the research context, and highlights the necessity of the research undertaken.

Chapter 2 presents a comprehensive review of current literature in fields of relevance to water and energy management. The focus of this thesis spans disparate fields of research (engineering and social science), and consequently literature from a range of disciplines was identified as relevant. To contextualise the contribution made by each article to the focus of this research - water-related energy management in urban households - a theoretical framework is developed, and discussion of the literature is presented within this framework. The chapter concludes with a summary of the gaps identified in the literature, and the implications that findings of current literature have for the research conducted in this thesis.

Chapter 3 provides an overview of the methodology adopted in undertaking research for this thesis. In particular, the chapter defines the scope of the research undertaken, outlines research objectives, and summarises the contribution that each research objective makes to the scope of the thesis as a whole. A brief overview of the methods applied to address each objective is given. The worldview of the researcher, and the influence that this has on the methodology adopted, is also discussed.

Chapters 4 and 5 are journal papers that have been published as outcomes of research undertaken for this PhD. The first paper (Chapter 4) details the quantification water-related energy use in seven households in urban Victoria, undertaken through empirical data collection and modelling of individual water-energy end uses within each household. In particular, the work identifies household characteristics which contribute most significantly to variations in the magnitude of water-related energy use between individual households. The second paper (Chapter 5) explores the range of potential energy use impacts of shower demand management in households described in Chapter 4. This work builds on the identification of household characteristics of significant influence for water-related energy use contributed in Chapter 4, by furthering understanding of their potential as levers for demand management.

Chapter 6 explores the potential for improved policy and regulation with a direct focus on household water-related energy (WRE) management in urban Victoria. Semi-structured interviews are employed to understand the perspectives of relevant actors within the existing institutional landscape, considering outcomes of Chapters 4 and 5, and questions of institutional change are addressed through consideration of the literature on transitions management and institutional entrepreneurship. The work highlights medium-term opportunities to create an enabling environment for policy practitioners in Victoria to improve management of water-related energy use in households.

The final chapter (Chapter 7) synthesises the findings of Chapters 4 to 6, in the context of the theoretical framework outlined in Chapter 3. Each specific research objective of the thesis is addressed, and recommendations for future research are made.

2. Literature review

2.1. Literature review methodology

The scope of the literature reviewed was defined to include only papers which addressed both water and energy. Journal database searches were conducted with a focus on two aspects:

- Papers which studied issues relating to water and energy end use in households; and
- Papers which explored issues relating to the integration of water and energy management policy and regulation.

The approach taken to reviewing literature was shaped by two broad questions:

- What do we need information about? (*Knowledge domains*)
- What kind of information do we need? (*Knowledge types*)

In addition to consideration of knowledge domains and knowledge types as outlined above, review of the literature was framed by a systems approach to policy intervention (drawing on the work of Meadows (1999)). A discussion of these aspects of the review – knowledge domains, knowledge types, and systems intervention points – is provided in sections 2.1.1 to 2.1.3. This is followed by a summary of the literature reviewed, identification of gaps in existing literature, and a discussion of implications for the research objectives of this thesis.

2.1.1. Knowledge domains – water-energy, human-physical

The mechanics of the urban water-energy system are described by both human attributes (e.g. behaviours, rules, economics, governance) and physical attributes (e.g. technologies, fittings, structures, environmental factors, infrastructure issues). These exist at micro (individual household) and macro (institutional/governance) scales, with a high degree of interaction. In concert, these attributes describe the way we manage and use water and energy. Knowledge of what these factors are, their comparative significance, and the way in which they interact to drive water-related energy use is an important foundation for the design of integrated management measures.

Figure 1 provides a conceptual illustration of the water, energy, physical and human domains of knowledge in the water-energy system. Examples of intersections between the domains are provided in Table 1.

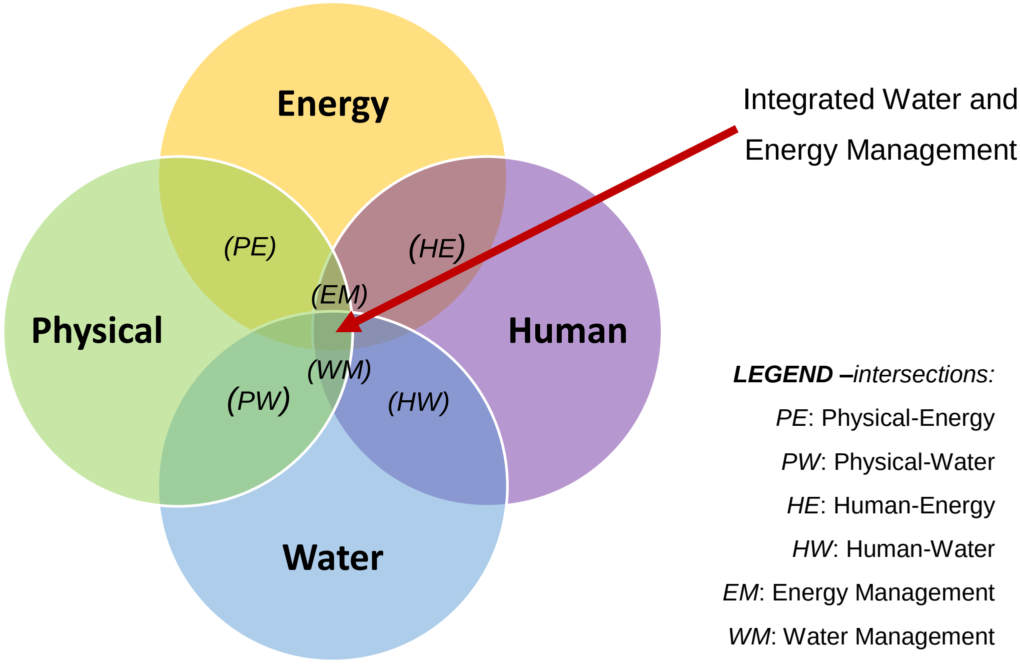

Figure 1: Conceptual diagram of knowledge domains in the residential water-energy system

Table 1: Examples of intersections between knowledge of water, energy, human and physical domains of the residential water-energy system

Abbrev.	**Knowledge intersection**	**Examples of system knowledge**
PE	Physical - Energy	• Energy efficiency of appliances • Temperature settings on appliances • Technical constraints on energy infrastructure • Heat loss characteristics of pipes • Peak capacity of energy transmission networks
HE	Human - Energy	• Frequency of electrical appliance use • Preferred settings for electrical appliance use • Electricity and gas tariff structures
PW	Physical - Water	• Flow rates of fixtures • Volume used per cycle of an appliance • Water treatment technologies
HW	Human - Water	• Frequency of use of water appliances, fixtures, fittings • Preferred settings for water appliance use • Water tariff structures

2.1.2. Knowledge Types – Descriptive vs Prescriptive

Critical reviews of industrial ecology as a field have noted that studies of material and energy flows (e.g. material flow analysis) provide descriptive information, and can be useful in setting goals for transition agendas (Korhonen 2004, Boons and Roome 2000). However, the predominant focus on the “what” in industrial ecology falls short of describing the “how” in terms of origins or solutions for achieving transition goals (Andrews 2003, Binder 2007, Binder et al. 2009). Both descriptive knowledge to assist in goal setting, and prescriptive knowledge to define actions to achieve these goals, are required for successful transitions (Korhonen 2004).

For the purposes of this research, the ‘knowledge types’ of prescriptive and descriptive knowledge have been defined, drawing on Korhonen’s definitions (Korhonen 2004). These types of knowledge, and their characteristics within the Physical and Human domains, are summarised in Table 2.

Table 2: Knowledge types in transition management

Knowledge Type	Physical Domain	Human Domain
Descriptive “How things are” or “The way things work”	The way in which physical/engineered components affect resource use	How policy-makers, decision-makers, organisations, firms and individuals act and behave; What their concrete actions and practical measures are.
Prescriptive “How things should be”	Changes to physical or engineered components required to achieve a particular goal.	How actors ought to /should behave to achieve a particular goal; Practical measures/actions that SHOULD be taken to achieve a particular goal.

2.1.3. Systems and intervention points

This research is based upon a systems view of urban water and energy management. The basic assumption of the work is that we are seeking to intervene in the urban water-energy system, to achieve a long-term goal of integrated water and energy management.

Specifically, the work draws on concepts put forward by Meadows identifying the places to intervene in a system ('leverage points'), and their relative effectiveness (Meadows 1999). In terms of relevance to the research proposed, the hierarchy of intervention points described in Table 3 has been adopted. These categories of intervention point, and in particular their relative effectiveness, have been adopted as a very generalised framework to guide research needs and should not be considered a definitive description of the system. Detailed whole-of-system mapping and analysis which would be required for such a description is beyond the scope of this research.

Table 3: Water-energy system intervention points

Intervention Point[1]	Examples within the urban water-energy system	Speed of impact	Effectiveness of intervention
Constants, parameters, numbers (e.g. subsidies, taxes)	Individual fixture and appliance specifications; individual behaviours	Faster	Lower
The structure of information flows (i.e. access to information)	Smart metering; consumer feedback; utility monitoring and reporting programs		
The rules of the system (e.g. incentives, constraints)	Building codes; design standards; tariff/concession structures		
The goals of the system	Regulatory reporting requirements; service provider charter/mandate		
The mindset or paradigm out of which the system arises	Resource efficiency; economic efficiency; consumer welfare; environmental sustainability	Slower	Higher

[1] Adapted from (Meadows 1999)

2.2. Summary of literature reviewed

A summary of the literature reviewed according to knowledge type (descriptive or prescriptive), knowledge domain (human or physical), and targeted intervention point is provided in Table 4. Discussion of the literature reviewed follows in sections 2.2.1 and 2.2.2.

Table 4: Summary of dimensions and types of knowledge encountered in literature

Type + Domain / Intervention Point	Descriptive Focus			Prescriptive Focus		
	Physical	**Physical + Human**	**Human**	**Physical**	**Physical + Human**	**Human**
Constants/ parameters	**E**, **F**, **H**, **K**, **L**, **O**, **Z**	**B***, **AC,** *AD,* **AE***, **AH**, **AI*, AS**	-	-	-	-
Structure of information flows	**I**, **AA, AM,**	*A, AG, AF*, AL, AR**	*J, N, P, AO, AK, AN, AJ*,* **AT,** *AU*	-	*AP*	-
The rules of the system	**C, D, G, AB***	-	*M*	-	**W**	-
The goals of the system	-	-	-	-	**U**, **V**, **X**, **Y**	*Q, R, S, T, AQ, AV*
The mindset or paradigm out of which the system arises	-	-	-	-	-	-

Bold *type denotes quantitative research, Italicized type denotes qualitative.*

**generalised prescriptive recommendations a minor focus of research*

A Newton and Meyer (2012)
B Kenway et al. (2013b)
C Nasrabadi et al. (2013)
D Zhou et al. (2013)
E Beal et al. (2012)
F Boait et al. (2012)
G Kenway et al. (2011b)
H Bohm (2013)
I Suh and Chang (2012)
J Strengers (2011b)
K Hernandez and Kenny (2012)
L Kar and Kar (1996)
M Hansen (1996)
N Strengers and Maller (2012)
O Lai et al. (2014)
P Martinez-Espineira et al. (2014)
Q Scott et al. (2011)
R Pittock et al. (2013)
S Hussey and Pittock (2012)
T Teschner et al. (2012)
U Rothausen and Conway (2011)
V King et al. (2013)
W Frijns et al. (2013)
X Siddiqi et al. (2013)
Y Kenway et al. (2013a)
Z Thur et al. (2006)
AA Truong et al. (2014)
AB De Coninck et al. (2014)
AC Shimoda et al. (2010)
AD Roulleau and Lloyd (2008)
AE Giglio et al. (2014)
AF Davis (2008)
AG Grieve et al. (2012)
AH Slys and Kordana (2014)
AI Naspolini et al. (2010)
AJ Kurz et al. (2005)
AK Fielding and Head (2012)
AL Horne et al. (2014)
AM Parker (2003)
AN Gilg et al. (2005)
AO Strengers and Maller (2012)
AP Stewart et al. (2018)
AQ Artioli et al. (2017)
AR Cominola et al. (2018)
AS Vieira et al. (2014)
AT Jeong et al. (2014)
AU Enshassi et al. (2017)
AV Al-Saidi and Elagib (2017)

2.2.1. Descriptive literature

2.2.1.1. Single domain focus (physical, or human)

Physical aspects

Literature focused on description of physical aspects of residential water-energy links was dominated by studies of hot water systems and of residential stock, fittings and design aspects, and by city-scale assessment of water-related energy consumption.

Studies of hot water systems focused on design characteristics and energy efficiency (Boait et al. 2012, Bohm 2013, Hernandez and Kenny 2012, Kar and Kar 1996, Lai et al. 2014, Parker 2003), energy savings potential through switching to solar hot water (Thur et al. 2006) and the use of demand-side management techniques to reduce primary energy use by using hot water systems as thermal storage for excess PV energy (De Coninck et al. 2014).

Of the hot water system studies focused on design characteristics and energy efficiency, Boait et al. (2012) examined the energy efficiency of five different types of hot water system employed in the UK for producing hot water for sanitation purposes. They demonstrated that electrical immersion hot water heaters show most potential as a low carbon method of water heating in the longer term, due to advantages when combined (as top-up heating) with a solar thermal hot water system. With a similar focus, Bohm (2013) contributed a study on the efficiency of domestic hot water systems as measured in 13 apartment buildings and two institutions in Denmark. They highlight that most energy demand in the measured buildings was lost in circulation systems (23% to 70% loss in apartment buildings), and propose a new type of hot water circulation pipe (co-insulated pipes) with a potential to reduce these heat losses by 40%. Hernandez and Kenny (2012) showed that the measured life cycle energy performance of domestic solar hot water systems was lower than predicted, based on a field study in Ireland. This contributed to less favourable (longer) energy payback periods than commonly noted in literature, and was attributed to the installation of oversized systems, installation and control issues, and combined use with efficient auxillary heating.

Studies of hot water system design characteristics also included work by Kar and Kar (1996), which examined the optimum design and selection of storage-type hot water heaters using parametric optimisation. Outcomes of their study demonstrate that a dual-tank hot water system of the same volume and power rating as a single-tank system (with the second tank comprising 25% of total volume and 75% of total power rating) would produce more hot water and use less energy (than the comparable single-tank system). Lai et al. (2014) offer an improved design for a wall-integrated solar hot water heater, based on experimental improvements to natural circulation loops for improved heat transfer. Considering hot water system design for different household configurations, Parker (2003) examined detailed household end use data from an electric utility load control program, showing that household occupancy has the strongest influence on variation in energy consumption for hot water heating, in addition to the insulation characteristics of the storage tank and the location of the tank within the air-conditioned (heated) area of the house.

The energy savings potential through switching to solar hot water heating was quantified by Thur et al. (2006) using measured and modelled data for oil- and gas- fired boiler water heating systems, and modelled impacts of switching to a solar hot water heating system. Outcomes show that potential fuel reduction could be much higher than the solar gain of the solar thermal system (due to boiler energy conversion efficiency losses).

De Coninck et al. (2014) explored the potential for rule-based demand-side management, for use as thermal storage for excess photovoltaic (PV) energy generation by modelling domestic hot water heat pump systems in 33 households. Outcomes showed that through application of only basic control algorithms to small tanks of 300 L volume, loss of potential PV energy generation (through shutdown at times of network oversupply) can be reduced by 74%, reducing net energy use at neighbourhood level by an estimated 3.4%.

Studies focused on physical aspects of residential water-energy links were also reviewed assessing the energy savings generated by water-efficient household stock and fittings (Beal et al. 2012). Beal et al. (2012) studied the water, energy, and greenhouse gas emission savings potential due to the installation of water-efficient household stock, using empirical water end-use data for over 200 households in Queensland, Australia. Outcomes showed that significant reductions in energy demand and carbon emissions were achievable through replacing an electric hot water system with a solar thermal system (with electric boost), and that installation of a low flow shower rose was the most optimal efficiency solution for increasing both water and energy savings.

With a focus on residential design characteristics, studies were reviewed assessing the energy use implications of district water heating designs (Truong et al. 2014) and energy and water demand implications of residential structural design (Suh and Chang 2012). Truong et al. (2014) modelled the impact of energy efficiency measures in buildings with district heating (for space and tap water heating) in Sweden. They showed that the impact of residential energy savings on primary energy use depended on district heating design, and that therefore it was essential to consider the interaction between end-use energy saving measures and supply systems for district heated buildings. Suh and Chang (2012) developed an energy and water demand estimation model for multi-family residential housing in Korea, using neural networks to identify eight influential factors predicting water and energy use (comprising factors related to temporal data, climate data, number of buildings, number of households, and spatial area).

Finally, within the physical domain, three city-scale assessments of water-related energy use were also observed (Nasrabadi et al. 2013, Zhou et al. 2013, Kenway et al. 2011c). Nasrabadi et al. (2013) present a case study of a region of Tehran (Iran), estimating the energy use reduction in response to water demand management. They show that water consumption management led to a reduction in water use in Tehran by 19% and highlight that this would consequently lead to reduced energy requirements for water service provision (excluding end use). Zhou et al. (2013) established a city-scale water flow analysis framework, and applied this to estimate the energy consumption of the water system in Changzhou, China. Data was collected through site visits, literature review and estimates, and outcomes showed that estimated energy consumption of the total water consumption for Changzhou was approximately 10% of city energy consumption, with the industrial sector responsible for 70% of this water-related energy use. Kenway et al. (2011c) offer a systematic review of Australian and international data to identify water-energy connections of influence, and provide a new conceptual model to estimate water-related energy use in a hypothetical city of 1 million people. They show that water-related energy use accounts for 13% of electricity use and 18% of natural gas used by the population for the average case, and that residential, commercial and industrial water-related energy use combined constitute 86% of water-related greenhouse gas emissions.

Human aspects

Studies focused on the human aspects of residential water and related energy use dealt primarily with determinants of habits, behaviours, perceptions and attitudes (Strengers 2011a, Strengers and Maller 2012, Martinez-Espineira et al. 2014, Fielding and Head 2012, Kurz et al. 2005, Gilg et al. 2005, Enshassi et al. 2017). Strengers (2011a) highlights the problems posed by a divide between energy and water production and the perceived separate sphere of consumption, arguing that production and provision of resources shape consumption and vice versa. They propose an alternate resource management paradigm central to which is the idea of moving away from management of resources to management of practices, and highlight that avenues for change include a focus on the intermediaries of demand (such as taps, showers, and appliances). Strengers and Maller (2012) also examine connections between resource provision and consumption, with a focus on the way in which energy and water security policies impact on households' capacity to adapt to climate change. Through a study of the experiences of Australian migrants, the authors characterise systems of energy and water provision in diverse countries, time and contexts, and the ways that resources enable or reduce resourcefulness, adaptive capacity and resilience. They conclude that by focusing on security policymakers reduce the capacity of households to adapt to climate change by prioritising immateriality, abundance, and homogeneity of supply, and that the characteristics of materiality, diversity and scarcity of supply are important and underutilised sources of adaptive capacity.

Several studies consider the determinants of household behaviours and habits. Martinez-Espineira et al. (2014) present an economic study based on household level data from Spain to examine factors driving household behaviours and habits and investment in water- and energy-saving equipment, showing that water and energy conservation habits and the purchase of resource-efficient appliances are not independent. Fielding and Head (2012) investigate the determinants of young Australians' environmental intentions and actions, through surveys of young people aged 12 to 17 (secondary schooling) and 18 to 24 (post-secondary schooling or workforce). The study showed that attributing responsibility for environmental protection to the community was associated with more positive environmental intentions and actions, that attributing responsibility to the government was associated with more negative environmental intentions and behaviour, and that young people with higher environmental concern and knowledge and a more internal locus of control regarding the environment reported stronger pro-environmental intentions and behaviour.

Kurz et al. (2005) applied a social-ecological framework to design an intervention to reduce residential water and energy use, studying the influence of information leaflets, attunement labels and socially-comparative feedback on water and energy consumption in 166 households in Perth (Australia). Attunement labels were found to lead to a 23% reduction in water consumption, whereas no significant reductions in energy use were observed as a result of any of the intervention methods. The authors suggest that the difference in water and energy use outcomes could be attributed to higher awareness of water use in the political context following recent drought conditions, and/or the tactile and visible nature of water use (comparative to energy). Gilg et al. (2005) studied 1600 households in Devon (UK), surveying everyday environmental action in and around the home to understand how different behaviours were related, and whether groups of individuals could be identified (through related behaviours) to define different sustainable 'lifestyles'. Results showed that relationships between actions existed, and that four types of environmentalist could be distinguished ranging from 'committed environmentalists' to 'non-environmentalists', and the authors highlight the environmental values, demographic characteristics and psychological factors of each of these groups to aid green policy formulation.

Enshassi et al. (2017) studied the perceptions of professionals on the drivers affecting water and related energy consumption in residential buildings in the Gaza Strip. Through the use of questionnaires based on drivers identified through literature review, the perceptions of 30 professionals were assessed. Results showed that respondents agreed on key drivers and that these drivers significantly affected household consumption of water and energy. The study identified seasonal weather changes, knowledge of water and energy conservation methods, and household size as the most important drivers of household water and energy consumption.

One study quantified the impact of water and energy use feedback on water conservation behaviours and related energy consumption in 18 residential dormitories in Virginia (USA) (Jeong et al. 2014), finding that programs focused on changing end user behaviour through combined water and energy use feedback were more effective than those targeting water use alone.

2.2.1.2. Dual domain focus (physical and human)

A number of studies were found which considered both physical and human dimensions in the same context. The majority of these focused on a single end use or appliance (eight of eleven papers), using a mixture of quantitative and qualitative methods.

Quantitative methods

Quantitative work considering both human and technical aspects most commonly addressed a single end use within the household, with a strong focus on hot water systems (Giglio et al. 2014, Shimoda et al. 2010, Naspolini et al. 2010, Vieira et al. 2014). Only one study reviewed provided quantitative analysis of all household water-related energy uses (Kenway et al. 2013b).

Two of the studies reviewed assessed the potential benefits of solar hot water systems for energy demand reduction in low-income communities in Brazil (Giglio et al. 2014, Naspolini et al. 2010). The first study deployed solar hot water systems with auxiliary electrical heating in sixty households, and monitored electricity demands for comparison with the status quo electrical resistance showerheads in thirty households. Outcomes indicated that solar water heating saved an estimated 200 kWh/residence annually, with a more than 2.6 kW reduction/unit in peak energy demands. The study noted that solar hot water systems therefore had the potential to assist low-income households in limiting electricity demand to less than the 220 kWh/month limit imposed in energy tariffs (Naspolini et al. 2010). The second study employed economic clustering techniques on low-income housing with solar hot water systems installed under government subsidy programs, to determine which socio-economic groups demonstrated most benefit from energy savings, and what impairments existed. Households with higher levels of education (at least high school level) and who were technologically savvy showed the highest energy reduction potentials, compared to low savings demonstrated by elderly households (Giglio et al. 2014). Impairments identified included difficulty understanding and using the technology (particularly in elderly households) and difficulty understanding the benefits of the technology when used among a set of other household technologies with a demand which exceeded the savings potential of the solar hot water system (Giglio et al. 2014).

An analysis of the performance of residential water heating systems in Brisbane (Australia) considered the impacts of hot water heating systems (solar with electric back-up, heat pump, electric) on the electricity grid and on level of hot water service provided (Vieira et al. 2014). Modelling of hot water system performance was based on empirical water use data from 27 households, using open access energy analysis software. Analysis comprised 54 scenarios based on water heating technology type, storage tank size, hot water consumption patterns, electricity supply tariffs, and clothes washer hot water supply source (internal or from hot water system). Key outcomes of the study included the finding that design of hot water heating systems should consider empirical demand patterns where possible to prevent perverse impacts from under- or over-sized systems. The study also concluded that in order to systematically optimise energy and service performance of hot water systems, the hot water tank size and electricity tariff selection should be considered in addition to specification of the type of hot water heating technology.

A Japanese study employed city-level energy end-use simulation modelling to assess the appropriateness of hot water system designs for primary energy savings in different household types (Shimoda et al. 2010). Hot water systems studied included gas instantaneous, electric storage, waste heat recovery condensing gas heater, solar hot water, micro gas engine co-generation system, polymer electrolyte fuel cell co-generation, and solid oxide fuel cell co-generation. The study found that optimal water heating units for each household type differed when considered from the point of primary energy use reduction, emissions reduction, or cost reduction (Shimoda et al. 2010).

Financial analysis of a drain water heat recovery unit installed in showers in Poland (Slys and Kordana 2014) found that showering time and water consumption affected unit financial performance, and that the design therefore demonstrated more benefit in a household with higher rotation of users (Slys and Kordana 2014). Payback period was assessed to be 2.5 years in the best possible scenario (low flow, long duration or frequent showering), however exceeded the technical lifetime of the device in less favourable scenarios.

Of the quantitative studies, only one study reviewed quantified and validated water- and energy-use impacts for all household end uses, through the application of material flow analysis for a single household (Kenway et al. 2013b). This study estimated the reduction potentials for water use, greenhouse gas emissions, water-related energy consumption, water costs and water-related energy costs were 4–77%, 14–85%, 15–93%, 1–31% and 13–90% respectively. The study also estimated that technical improvements alone would result in less than a 15% change in terms of energy and greenhouse gas emissions[1], concluding that behavioural changes would be required for greater impact.

Qualitative methods

Qualitative studies reviewed were concerned primarily with understanding the drivers behind adoption of efficient stock and habits (Roulleau and Lloyd 2008, Grieve et al. 2012, Newton and Meyer 2012, Horne et al. 2014) and residential water-electricity demand profiles (Cominola et al. 2018), and the interrelationship between efficient stock and efficient habits (Davis 2008).

Uptake of solar hot water systems in New Zealand was investigated by two of the papers reviewed (Roulleau and Lloyd 2008, Grieve et al. 2012). Interviews were conducted by Grieve et al (2012) in six households to examine the decision processes of householders replacing hot water systems or building new homes, in addition to interviews with

[1] Excluding a switch to a solar hot-water system.

tradespeople and professionals advising the households. Findings were that (a) decision processes were found to be consistent across the households regardless of context, (b) support from suppliers regarding energy efficiency was noted as lacking, (c) available information on energy efficiency was viewed as impartial, confusing and irrelevant, and (d) the simplicity and convenience of technologies currently in use is a strong disincentive to change to more efficient models (Grieve et al. 2012). A review of a New Zealand solar hot water system subsidy program, and comparison to similar international programs, found that the inclusion of both minimum performance criteria and price criteria were important for subsidy programs, to prevent adoption of low-efficiency models and to encourage cost effectiveness (Roulleau and Lloyd 2008). The review also found that policies have been most successful where the subsidy is significant compared to the cost of the system (Roulleau and Lloyd 2008).

The link between clothes washer efficiency (including washing machines) and user behaviour was explored by Davis (2008) based on empirical data from a field trial of high efficiency clothes washers in the United States. Through the use of an economic model (household production model), it was demonstrated that only a small portion of the gains in resource use efficiency are offset by increased usage (encouraged by lower operating costs) (Davis 2008). It was also demonstrated that time-intensive processes (such as clothes washing) are less prone to increased usage responses in higher efficiency appliances (Davis 2008).

Two papers sought to understand the drivers of patterns in household consumption and use. The social drivers behind home water and energy efficiency retrofits and renovations were examined in a paper by Horne (2014), based on interviews with home owner renovators and project managers in Australia. Horne found that although government programs have encouraged new ‘green’ renovation businesses, approaches have been inconsistent and more care is needed in program design for the residential building industry (Horne et al. 2014). Green building regulations were recognised as an opportunity for more consistent support. The study also found that the small nature of most renovation businesses led to experience-based skills and capabilities, and unstructured learning and support processes (Horne et al. 2014). The study concluded that more attention is needed on the interdependence between homeowners with ‘green’ aspirations and the industry capable of meeting these needs.

The second study into patterns of household consumption (Newton and Meyer 2012) employed economic analysis (linear regression) techniques on data for 1,250 Melbourne households, to highlight the relative impact of individual and contextual influences on water and energy use, travel, housing, and appliance. The study concluded that (a) determinants of consumption vary for different categories of household resource use, and (b) individual attributes (structural and attitudinal) were found to be less influential than contextual factors (household, dwelling, location) when accounting for overall resource use. A key finding of the study was that small or single-person higher income households were correlated with high consumption in water, energy, housing and appliances to a much higher degree than other socio-demographic groups (Newton and Meyer 2012). A trend towards higher water use in the elderly was also observed.

Cominola et al. (2018) contribute a case study on customer segmentation analysis to support customised residential water-electricity demand-side management programs. The analysis was based on water and electricity data for 1107 residential properties in Burbank, California, in addition to corresponding survey data on psychographic features including occupant demography, household characteristics, and water and energy consumption attitudes and preferences. Key aims of the study were to explore the heterogeneity of water-electricity demand profiles and, through application of statistical techniques (such as principal component analysis), segment customers into clustered water-electricity demand profiles and identify key aspects associated with each profile. Findings included a linear correlation between average water and electricity demands, and that therefore high-using customers can be targeted with the intent to coordinate water-energy management efforts. However, the work also noted an absence of a relevant causal nexus between water and electricity use daily load shapes, and that therefore in management interventions water demand management actions should be differentiated from those for electricity demand management. Both objective (e.g. ownership of a swimming pool) and subjective (e.g. conservation attitudes) were found to be relevant potential drivers of user water-electricity demand profiles. The authors highlight the opportunities afforded by advanced metering infrastructure for the design of customised demand management strategies, and provide a number of recommendations for the development of the same. They note that analysis would be strengthened significantly by availability of consumption data measured or estimated at end-use level.

2.2.1.3. Summary of descriptive literature

In general, descriptive studies were targeted at the shorter-term intervention points within the system. The predominant focus was on information for intervention in the rules of the system, in the form of general recommendations for:

- subsidies or rebates for hot water systems (Naspolini et al. 2010, Grieve et al. 2012, Shimoda et al. 2010, Roulleau and Lloyd 2008, Giglio et al. 2014);
- water demand management policies (Nasrabadi et al. 2013, Zhou et al. 2013, Kenway et al. 2011c) to reduce water-related energy use;
- suggestion of energy pricing as a strong lever to reduce water use in Denmark[2] (Hansen 1996);
- highlighting economic incentives (such as subsidies) to defray cost of investment in water and energy efficient appliances (Martinez-Espineira et al. 2014);
- industry training programs and support (Horne et al. 2014); and
- consumer education programs (Newton and Meyer 2012).

Several studies extended beyond the purely descriptive, providing some recommendations for specific management water-related energy management opportunities. These included retrofitting and rebate policies to target specific water and energy efficient appliances (Beal et al. 2012, Naspolini et al. 2010, Giglio et al. 2014) and end uses (Kenway et al. 2013b), and a demand-side management program to reduce primary energy use through thermal storage of PV energy in hot water system storages (De Coninck et al. 2014).

2.2.2. Prescriptive literature

2.2.2.1. Reviews

Rothausen and Conway (Rothausen and Conway 2011) contribute a high level review of the international water sector. The paper focuses on identifying key energy uses within water sector processes, and the current state of knowledge to describe them, followed by a discussion of boundary-setting issues for analysis of energy use by the water sector. The work finds that common approaches limit understanding to direct energy use within the water sector and exclude the consideration of end use, despite research in the US (Griffiths-Sattenspiel 2009) and the UK (DEFRA 2008) which identify end use as the most significant component of water-related energy use (Rothausen and Conway 2011). The authors highlight a knowledge gap at the interface between water and energy, noting that most knowledge is limited to grey literature, in addition to a separation of water and energy policies as key challenges (Rothausen and Conway 2011).

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[2] Differences in environmental context will have implications for the transferability of these results to other regions.

At a similarly high level of analysis, a comprehensive review of issues, knowledge and approaches to coherence in water and energy policy was conducted with a specific focus on the United States, in addition to some consideration of the international context (King et al. 2013). The paper lays out challenges and gives examples of mixes of technology and policy which meet water and energy objectives, identifies gaps inhibiting future policy development, and discusses key findings. Technologies which are noted as important for water-energy interaction include low flow fixtures, energy efficient appliances, distributed rainwater collection, solar water heating, and approaches which encourage peak load shifting or shaving (i.e. reductions) (King et al. 2013). The authors note the success of data collection and generation of descriptive knowledge at bridging institutional gaps, but question the effectiveness with which accurate data and integrated regulatory frameworks translate to better policy (King et al. 2013). The review also includes case studies of water and energy policy integration in the US and internationally, including Australia. In the US, a diversity of roles and agencies in both water and energy management is noted as a challenge, in addition to a difference in the vertical hierarchies for policy-making (top-down for the energy sector, bottom-up for the water sector) (King et al. 2013). The authors also note that in Australia, proactive water policy has been driven by water scarcity, while energy policy has lagged due to relative abundance. Fragmentation in water resource data is also a noted challenge (King et al. 2013). Key findings of the review note a serious lack of data to inform policy, but highlight the opportunity in potential synergies between water-conservation and energy-conservation policy (King et al. 2013).

A review of water-energy-food nexus literature by Al-Saidi and Elagib (2017) aimed to understand justifications given for the need for a nexus approach, and to identify tools available for analysis of nexus issues which allow for integrated consideration of science and policy aspects. The authors found that three key drivers underpin the call for a nexus approach: increasing resource inter-linkages due to scarcity; recent resource supply crises; and the failure of sector-driven management strategies (such as Integrated Water Resources Management). The review noted that nexus approaches have been successful in changing policy debates, but that issue prioritisation is missing. The authors also find that nexus governance is so far missing from the nexus debate. Recommendations of the work include a need for tools experimentation and development at each level of the policy cycle. Of particular relevance to the current work, the authors highlight that the water-energy-food nexus should be translated through more case-study based recommendations into the reality of institutions, bureaucracies and environmental stakeholders, avoiding generalisation and the pursuit of an ‘ultimate model’ for institutional integration (Al-Saidi and Elagib 2017).

Political and governance implications of the water-energy-food nexus are further examined by Artioli et al. (2017). The focus of the work is on making explicit the links between a water-energy-food nexus policy framing and the frameworks of urban policy making. The authors aim to ‘urbanise’ the nexus approach to explore governance implications for cities, arguing that much of the water-energy nexus policy framing in literature to date has focused on either macro-level dynamics (national or international) or place-specific studies. Consequently, they aim to put forward a mid-range approach between these two contexts. The authors also extend their analysis to development of a set of hypotheses about interplay between the nexus approach to cross-sectoral integration and urban governance, discussing power scales, state/market relations, and tools of urban governance. Discussion of the urban focus takes two approaches: the process of urbanisation as a cause of nexus issues (as manifestation of forces perpetuating intensification and growth, and as an aggregated demand for resources); and acknowledgement that nexus problems take on specific characteristics in cities, as the concentration of population, consumption, infrastructure and social needs affect the availability and interdependence of water-energy-food in specific ways. The authors find that research largely overlooks interplay between water-energy-food issues and urban governance, and that the nexus approach offers potential as a driver for policy change which can assist in structuring alternatives (rather than provide a panacea). In particular, they note directions for future research around the question of which actors have authority and capacity for integrated management, with attention to financial, material and political resources and tools for policy change.

2.2.2.2. Case studies

Four of the papers reviewed described case studies of approaches with strong links between physical and human system attributes, and a clear prescriptive focus (Frijns et al. 2013, Kenway et al. 2013a, Siddiqi et al. 2013, Stewart et al. 2018). A case study on master planning processes by Dutch water boards to achieve an energy-neutral urban water cycle describes a process in which an assessment of the water and energy balance through the water cycle, following by identification of energy optimisation opportunities, was used as the basis for stakeholder engagement ‘to internalise the need for implementation’ through master planning (Frijns et al. 2013). The work highlights the limited effectiveness of water industry supply-side measures, and highlights the needs and opportunities for multi-disciplinary collaboration with the housing, energy, agriculture and industrial sectors, including a need to consider energy use associated with domestic water end use (Frijns et al. 2013).

An approach to improving integration in water and energy planning through supporting bridging between inter-organisational decision networks is described through a case study in Jordan (Siddiqi et al. 2013). Local physical resource inter-linkages were quantified, following which stakeholder networks were assessed to identify key actors and organisations. Based on organisation theory, 'boundary spanning agents' (at the interface between communities of knowledge-generating experts, and communities of decision makers) were identified to support the application of knowledge for management action. Key findings highlighted three options to support inter-organisational consistency for water and energy management, which were (1) leveraging existing links between individual actors, (2) creating new roles or organisations, or (3) restructuring or merging existing organisations. When describing options to leverage existing links, the author identifies high-level political influence (e.g. King, Prime Minister) important in setting common drivers across water-energy sectors, but notes a lack of expertise at this level to propose detailed plans; the necessary expertise exists in the separately administered water and energy sectors (Siddiqi et al. 2013). The role of research organisations is also highlighted as important in generating necessary cross-sector knowledge, but lacking the power to drive influence (Siddiqi et al. 2013).

The third paper describing work with strong physical and human components and a clear prescriptive focus details a stakeholder engagement process to set common goals for water-related energy management in California (Kenway et al. 2013a). The aim of the work was to improve understanding of the necessary actions and research required for management of urban water-related energy, through collaborative work with water and energy stakeholders. Outcomes essentially provide a framework to guide research needs, with policy and action needs a lesser focus (Kenway et al. 2013a). Recommendations of the work highlighted needs for consumer education, standards, guidelines, increased funding and planning support, research to better understand consumer motivations, and improved accounting and monitoring frameworks to track water-related energy use (Kenway et al. 2013a). Benefits of engagement and cross-sector collaboration were recognised by the participants to have (1) increased understanding of the water-energy problems to be addressed, (2) identified key objectives to clarify what their organisation decisions should achieve, and (3) defined a rich set of alternatives (Kenway et al. 2013a).

Stewart et al. (2018) focused on water-energy nexus case studies to provide a vision of an integrated multi-utility service provider, which they argue could provide user-friendly platforms to feed water, electricity and gas data to customers and utilities, allowing customers to ‘unpack the water-energy nexus’. The emphasis of the paper is on the opportunities afforded by advanced metering technologies coupled with informatics. Four case studies of digital metering technology, applied for the concurrent collection and modelling of multi-utility data, are provided in urban water-energy management contexts. Case studies included household level analysis of water-energy data to understand shower use consumption trends, residential water-electricity customer segmentation analysis for targeted water-energy conservation initiatives, the use of a web interface to provide water-energy consumption feedback and conservation opportunities to customers, and analysis of rain tank water and energy use events. Benefits of digital metering and informatics approaches were highlighted through these case studies including the ability to create targeted demand-side management programs, the capacity for household level information and feedback, better understanding of water and energy use profiles and key determinants, and an ability for utilities to assist in optimising customer systems. Stewart et al. (2018) further outline a vision of the features of an integrated multi-utility service provider, and provide and research and development agenda to support the realisation of this vision. They highlight strategy needs, including a need for institutional (regulatory and market) hurdles to be addressed to foster water and energy collaboration, in addition to technological and information needs. The authors highlight that these strategic, technological and information needs must all receive attention before the vision of a digital multi-utility service provider can be realised.

All four papers discussed above contributed valuable demonstrations of approaches to encouraging cross-sector collaboration to improve consistency in water-related energy management. Recommendations focused primarily on high-level research and governance needs, and gaps exist in prescription of practical actions for implementation at more immediate-term intervention points. In part this stems from the broad scope of the papers, three of which focus on the national or state level and on implications for the whole of the supply side of the water and energy sectors, with the fourth focused on a longer-term vision for transition to a new form of multi-utility service provision. Prescription of concrete, practical actions for the immediate-term will require work which is highly context-specific. There is significant potential for valuable work prescribing practical action at shorter-term intervention points.

2.2.2.3. Common issues recognised in prescriptive literature

Several themes were consistently recognised across the prescriptive literature. These were:

- **The nature of the water-energy integration issue as a 'wicked problem'.** Australian literature highlighted the complexity and uncertainty associated with environmental issues, including differing values and contested methods, challenges of working across scales, and lack of clarity of responsibilities, all of which were recognised to contribute to sustainable development failures through limited capacity to manage them (Pittock et al. 2013). Research in the US similarly recognised the heightened complexity and exacerbated trust and confidence issues that arise through combing water and energy issues, highlighting an emphasis on alternatives, scenarios, and stakeholder interaction as a means to overcome this (Scott et al. 2011).
- **Dominant focus on technical solutions to date.** A number of authors emphasised a need to include institutions and decision making when addressing the water energy nexus, and avoid viewing it as a purely resource management issue to be solved by technical approaches (Scott et al. 2011, Hussey and Pittock 2012).
- **Fragmentation in institutional decision making**. Authors recognise inconsistency and opposing tendencies in water and energy management approaches (Hussey and Pittock 2012), (Scott et al. 2011), stemming from a separation between environmental management, policy and regulation, and commercial water supply and wastewater treatment (Rothausen and Conway 2011). A need is identified for stronger cooperation and consistency between environmental targets and water supply strategy, and energy efficiency and climate change policy (Rothausen and Conway 2011). To support this, it is highlighted that environmental policy needs to be capable of evaluating and integrating policy measures across sectors (Pittock et al. 2013). It is noted that the need for institutional change is likely to be resisted by key actors with power under current arrangements (Teschner et al. 2012). Examples of integrated, coherent energy-water policies are noted to be lacking, for which coordination of planning and allocation of responsibilities is needed (King et al. 2013).

- **Need for reporting approaches and frameworks to account for water-energy impacts.** Externalisation of water-energy impacts is recognised as a key issue preventing integrated decision making (Hussey and Pittock 2012, Scott et al. 2011). As an example, a study of measures for urban water conservation in California found that some water-saving household appliances only prove cost-effective when energy savings are included (Rothausen and Conway 2011). The extent to which policy makers can look past dominant goals (e.g. economic cost) to understand broader impacts (e.g. on water resources) will depend on the extent to which appropriate measures are in place to 'internalise' impacts (Pittock et al. 2013).
- **Limited focus on end use.** Policy focus was observed to neglect regulation and requirements for end use of water. Legislation to ensure water efficiency in the home was noted as lacking (c.f. energy efficiency for building codes), and authors highlighted that a disregard for the importance of consumer behaviour and demand management is evident in policy and published literature (Rothausen and Conway 2011).
- **Limited focus on urban governance.** Literature notes that the interplay between water-energy-food nexus issues and governance has largely been overlooked (Artioli et al. 2017, Al-Saidi and Elagib 2017), in particular urban governance (Artioli et al. 2017). Recommendations include a need for research around the question of which actors have authority and capacity for integrated management (Artioli et al. 2017), and a need for more case-study based recommendations into the reality of institutions, bureaucracies and environmental stakeholders, avoiding generalisation and the pursuit of an 'ultimate model' for institutional integration (Al-Saidi and Elagib 2017).

2.3. Gaps in literature

The following knowledge gaps were identified through literature review:

- The majority of quantitative work of a descriptive nature focused on a single end use within households, with a dominant focus on hot water systems.
- Few descriptive studies considered the potential for energy management through water efficiency (Beal et al. 2012, Kenway et al. 2013b).
- There are limited descriptive studies which quantify both human and physical factors in defining the water-related energy opportunity in households, despite a

recognised need in literature (Scott et al. 2011, Hussey and Pittock 2012). Only one study was observed quantifying and validating the influence of both physical and human aspects for all household end uses, for a single household (Kenway et al. 2013b). While an important contribution to understanding household water-energy links, it is difficult to draw conclusions for broader goal-setting without an understanding of whether results are representative.

- Descriptive work focuses on generating knowledge for shorter-term interventions but lacks identification of concrete and practical actions to translate this knowledge to management implementation. Similarly, prescriptive studies focus on high-level institutional issues but lack identification of concrete and practical actions that can be taken in the shorter-term. While the work to date in both areas is valuable and essential to build towards long-term integration goals, a gap exists in the prescription of action to take advantage of current opportunities in water-related energy management.

2.4. Implications for research objectives

Implications for research objectives for this project include:

- Barriers to integration include sectoral fragmentation and incoherence, and opposing tendencies (Hussey and Pittock 2012, Scott et al. 2011, Rothausen and Conway 2011, King et al. 2013). The research approach should include an understanding of how the structure of the system supports or constrains water-related energy management goals.
- The nature of water-energy integration issue as a wicked, complex problem suggests that best approaches would focus on stakeholder interaction and communication of scenarios and alternatives (Scott et al. 2011).
- Consideration of policy issues should consider questions such as which actors have authority and capacity for integrated management (Artioli et al. 2017), and should take a case-study approach (Al-Saidi and Elagib 2017).

3. <u>Methodology</u>

3.1. Introduction

This chapter provides an overview of the methodology applied in the development of this thesis. This includes an acknowledgment of the worldview of the researcher and the corresponding influence this has had on research design and methods selection. The chapter then outlines the theoretical underpinnings of the research approach adopted and how the research objectives fit within this theoretical framework. This is followed by definition of the scope of research inquiry, and an overview of methods applied in answering each of the research objectives within that scope.

3.2. Research approach

3.2.1. Researcher worldview

The research approach adopted for this thesis is based on the pragmatist worldview as defined by Creswell and Creswell (2018). Under this definition, pragmatism involves a primary emphasis on the research problem and the use of any approaches available to understand that problem, including both quantitative and qualitative approaches. The pragmatist approach is reflected in my choice of research methods, which include both material flow analysis (quantitative) and stakeholder interviews (qualitative) focused on the problem of water-related energy management in urban households.

My research approach is influenced by my professional background as a process engineer in the Australian water sector, with several years of experience in water supply infrastructure planning and policy. My professional experience has comprised a dominant focus on process-focused and quantitative approaches to understanding resource flows. The general objective of my professional work has been to support the design of infrastructure and policy for resource management. Management goals supported by this work have typically encompassed quantitative resource (water, energy, carbon) flow targets, financial cost-benefit targets, and supply security and reliability goals (i.e. constancy of supply).

My professional background influences my research approach in two key ways. In the first, it biases the scope of my research inquiry towards consideration of the quantitative impacts of policy upon resource flows. Other qualitative impacts such as social or economic value (beyond cost) are not captured. It is acknowledged that these impacts are important, and further research to consider them would be valuable. To this end, I have endeavoured to recognise the ‘human’ dimensions of resource flows with the aim of facilitating better connections with social research by others qualified in this domain. The second key impact upon my research approach is an expansion of the scope of my research problem beyond the quantification of resource flows, to include consideration of the institutional dynamics of policy development for resource management. This approach comes from the observation of a disconnect between quantitative data typically provided to influence decision making in resource policy, and the scope of the decision that any one actor using that data is able to influence within the constraints of their institutional setting.

3.2.2. Scope

The scope of this thesis is limited to consideration of household water-related energy use in urban Victoria.

This thesis is designed to contribute towards a longer-term goal of increased integration in water and energy management, a need for which has been highlighted in academic literature (see section 2.2.2). This aim forms one step towards the greater goal of achieving greater integration in all resource management, resolution of which will require significant research efforts at a scale and complexity well beyond the scope of this thesis. This thesis instead intends to support these goals by building up a foundation of logical argument, presented as a flow of hypotheses in Figure *2*. These hypotheses are mapped against their corresponding point of intervention within urban resource management as a system (as discussed in Section 2.1.3 of this thesis).

The scope of this thesis contributes towards long-term goals by generating knowledge to support the foundational hypotheses i), ii), and iii), as illustrated by the red dashed boundary in Figure *2*. The work intends to explore management policy options to inform shorter-term pragmatic action (focused on individual water-energy parameters, and information flows and system rules), while providing insight to contribute to longer-term goal-setting and ultimately a shift to a paradigm of integrated resource management.

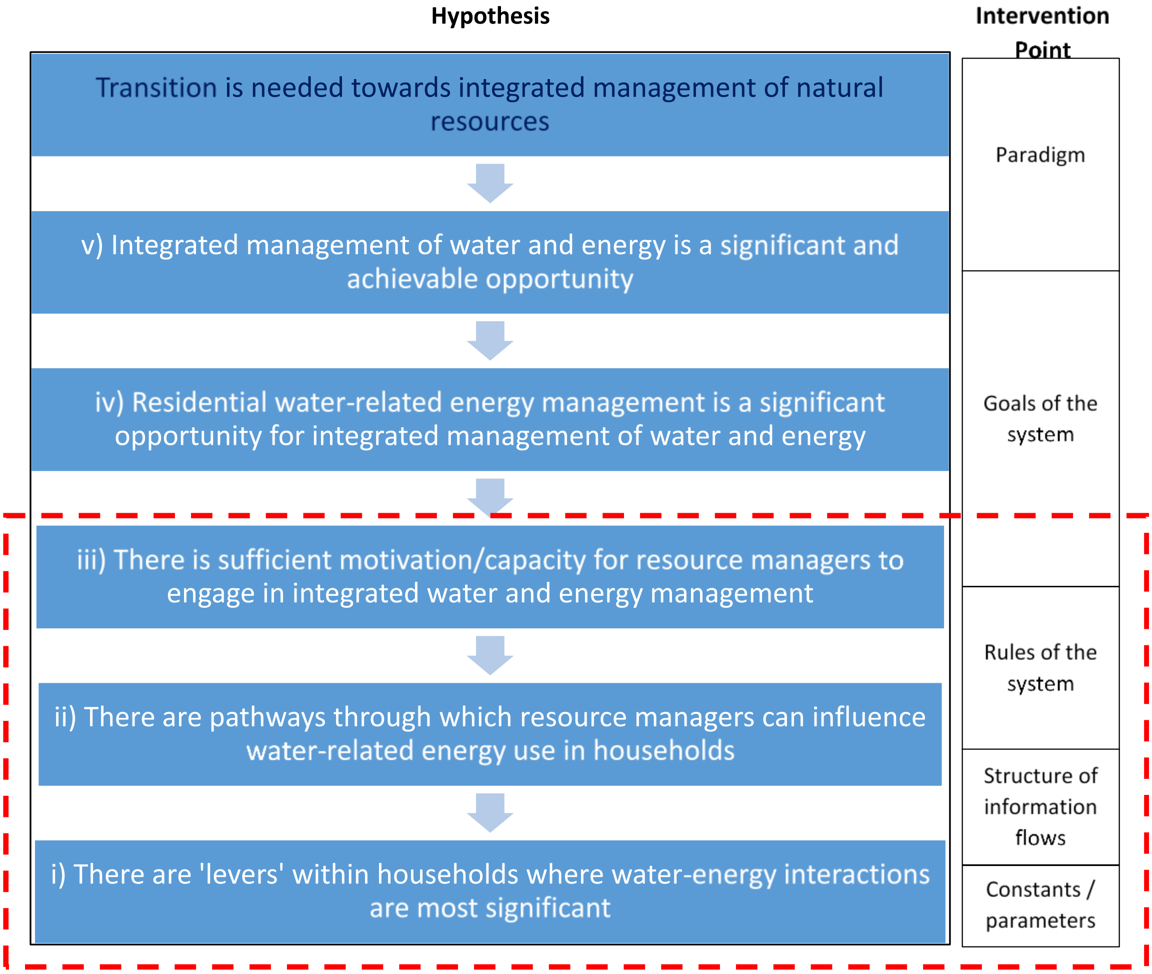

Figure 2: Flow of hypotheses building to a transition towards integrated resource management. Dashed red line encompasses the scope of contribution of this project.

Behaviour change and demand management are significant fields of research with strong implications for resource (e.g. water and energy) management policy, particularly in the context of household end use. The scope of this thesis has been explicitly designed to exclude consideration of psychological / behavioural modification as it relates to water and energy consumption, for the following reasons:

- the depth and rigour required to address these aspects appropriately would expand the scope of the work beyond that practically achievable in a single thesis;
- based on advice from experts in these fields, it was concluded that these aspects are more appropriately addressed by researchers more qualified to do so; and
- the scope of this thesis already comprises a substantial body of work.

In recognition of the importance of behaviour change and demand management in achieving the longer-term goals of this work, however, the scope of research was designed to provide robust data to inform worthwhile pathways for behaviour change and demand management work which could then be conducted by those better qualified in this area. This was achieved primarily through consideration of ‘human’ dimensions of resource flows, as outlined in section 3.2.1.

3.3. Research objectives

Three key research objectives have been defined within the scope of this thesis, as follows:

- **Objective 1** – Quantifying WRE use in individual households, and identifying household characteristics which contribute significantly to variation.
- **Objective 2** – Quantifying impacts of a water demand management scenario, and identifying influential factors leading to differences in impacts between households.
- **Objective 3** – Exploring the potential for policy and regulation for household WRE management in urban Victoria.

Each research objective is addressed separately as chapters 4,5 and 6 of this thesis. These objectives, and their contribution to each of the hypotheses highlighted within scope in Figure *2*, are summarised in Table 5. Key aspects of the research methods adopted are also summarised.

Table 5: Summary of research objectives, research questions, and methods against research scope items (hypotheses)

<table>
<tr><th rowspan="2">Hypothesis</th><th>Chapter 4</th><th>Chapter 5</th><th>Chapter 6</th></tr>
<tr><td>Objective 1: Quantifying WRE use in individual households, and identifying household characteristics which contribute significantly to variation.</td><td>Objective 2: Quantifying impacts of a water demand management scenario, and identifying influential factors leading to differences in impacts between households.</td><td>Objective 3: Exploring the potential for policy and regulation for household WRE management in urban Victoria</td></tr>
<tr><td rowspan="2">(i) There are 'levers' within households where water-energy interactions are most significant</td><td>1a) How consistent is the magnitude of WRE use, and associated utility costs and GHG emissions, in different individual households?</td><td rowspan="2">2b) What impact does the type of hot water system installed have on energy use for hot water heating?</td><td rowspan="2"></td></tr>
<tr><td>1b) How consistent are the key household characteristics which drive this variation (i.e. individual end uses, and the human and physical characteristics describing their water and energy use)?</td></tr>
<tr><td rowspan="3">(ii) There are pathways through which resource managers can influence water-related energy use in households</td><td rowspan="3">1c) What implications do these key characteristics have for integrated management of household water and related energy use, costs and GHG emissions?</td><td>2b) What impact does the type of hot water system installed have on energy use for hot water heating?</td><td rowspan="3">3c) What are the views of key stakeholders on potential policy change for improved household WRE management, in particular the opportunities presented by a WRE policy focus (and likely barriers to the same)?</td></tr>
<tr><td>2a) What is the potential water and energy saving associated with a four minute shower water demand management program?</td></tr>
<tr><td>2c) What is the combined water and energy cost saving to the household as a result of the demand management scenario?</td></tr>
<tr><td rowspan="2">(iii) There is sufficient motivation/capacity for resource managers to engage in integrated water and energy management</td><td rowspan="2"></td><td rowspan="2"></td><td>3a) Who are the key stakeholders with an influence on water and energy use in households, and for what reason (objective) and how (mechanism) do they exert this influence?</td></tr>
<tr><td>3b) For these stakeholders, what have been the key enabling factors in past experiences of policy innovation, and what strategies have been employed?</td></tr>
<tr><td>Research Methods</td><td colspan="2">Empirical data collection and analysis (7 x individual households) of household water and energy use characteristics; Mathematical material flow analysis (MMFA) modelling of individual water and energy end uses within each household.</td><td>Semi-structured interviews (17 participants); Thematic analysis informed by theory from socio-technical systems, transition theory, transition management, and institutional entrepreneurship literature.</td></tr>
</table>

A brief description of each research objective, the methods adopted, and the intended outcomes is provided in sections 3.3.1 to 3.3.3.

3.3.1. Objective 1 – Understanding variation in WRE use between households

The first research objective explores the impacts of differences between individual households on water-related energy use, costs and emissions. Specifically, the following research questions are addressed:

a) How consistent is the magnitude of WRE use, and associated utility costs and GHG emissions, in different individual households?

b) How consistent are the key household characteristics which drive this variation (i.e. individual end uses, and the human and physical characteristics describing their water and energy use)?

c) What implications do these key characteristics have for integrated management of household water and related energy use, costs and GHG emissions?

This research objective was addressed through mathematical material flow analysis modelling, using the validated ResWE model developed and published by (Kenway et al. 2013c). The ResWE model focuses on individual water and energy using subsystems within a household (i.e. shower, bath, clothes washer, indoor taps, dishwasher, outdoor, toilet, kettle, air-conditioner, and an 'other' category for non-water related energy uses). Outputs of the model include water use, energy use, water and energy costs, and embodied greenhouse gas emissions as a result of energy use. These outputs are broken down into individual components of subsystems, including energy losses. The detailed breakdown of water and energy use, costs and emissions for each household end use (model outputs) allows exploration of the key contributing factors for differences in WRE use between individual households, and further links these to differences in physical and human attributes (model inputs).

To inform model parameters, a detailed empirical dataset was collected defining the structural, environmental, behavioural and occupancy characteristics of seven individual households (two in Brisbane, five in Melbourne), and water and energy supply details. Data was collected in person through household audits in March 2013, focused on characteristics of each household over one historical calendar year (April 2012 – March 2013). Audit data was then analysed to develop an input dataset of 139 parameters for each household studied, representing water and energy end use on an average day annually. This dataset was used to develop a ResWE model for each household.

ResWE model outputs were then analysed to determine key differences between water use, energy use, GHG emissions and costs between individual households. The end uses contributing most to this variation were identified, and key household characteristics (e.g. behaviours, appliances, fittings) driving these differences were investigated.

Outcomes of this research objective are intended to support policy development by identifying key points of influence for water-energy interaction within households.

3.3.2. Objective 2 – Gauging the effect of household water demand management on WRE use

Research Objective 2 builds upon Objective 1, by exploring the potential for water demand management (through a focus on showering) as an energy management measure. The first research objective demonstrated the significance of the complexity in differences between behaviour and technology between households, highlighting the impacts that such differences have on WRE use. Previous quantification of the potential for water-related energy demand management has not considered the complexity of differences in both behaviour and technology between households. Building on the findings from Research Objective 1, Objective 2 assesses the impact that a behaviour-focused water demand management scenario would have in the households studied, and the impact that technology type (hot water systems) would have upon these outcomes, by asking the following questions:

a) What is the potential water and energy saving associated with a four minute shower water demand management program?

b) What impact does the type of hot water system installed have on energy use for hot water heating?

c) What is the combined water and energy cost saving to the household as a result of the demand management scenario?

Existing ResWE models used in Objective 1 were adopted for use in scenario analysis. Scenarios were designed and applied to determine the following: i) the impacts of a four-minute shower scenario on water use, energy use and related costs (in comparison to existing baseline established in Objective 1); ii) the influence of hot water system types on

WRE use for the baseline and four-minute shower scenarios; and iii) the fixed and variable water and energy cost impacts of the above.

Outcomes of this research objective are intended to gauge the significance of potential WRE use savings in response to demand management, to support development of management policy.

3.3.3. Objective 3 – Exploring the potential for policy and regulation for household WRE management in urban Victoria

The third research objective explores the potential for policy and regulation with a direct focus on household WRE management in urban Victoria. In essence, this objective focuses on the shorter-term ways in which key actors might begin to initiate change towards household water-related energy management, as a foundation for a longer term transition. Specifically, this objective focuses on the following research questions:

a) Who are the key stakeholders with an influence on water and energy use in households, and for what reason (objective) and how (mechanism) do they exert this influence?

b) For these stakeholders, what have been the key enabling factors in past experiences of policy innovation, and what strategies have been employed?

c) What are the views of these stakeholders on potential policy change for improved household WRE management, in particular the opportunities presented by a WRE policy focus (and likely barriers to the same)?

Semi-structured interviews were conducted with key 17 key stakeholders, including participants from water utilities (bulk and retail), energy distribution and retail companies, state government departments, local governments, independent regulatory bodies, community organisations and industry professional organisations. Participation was sought from organisations with an interest in the management of water or energy use in households. Participants were initially identified through previous involvement in earlier stages of the research project, following which the ‘snowball’ method was used to identify further participants for involvement. Interviews were conducted in person for approximately 1 hour, and were audio recorded and transcribed. Thematic analysis was then used to explore common themes in interview responses, and these themes were summarised to form responses to research questions (a) to (c) above.

Analysis of interview transcripts was informed by a conceptual framework based on literature on socio-technical systems, transition theory, transition management, and institutional entrepreneurship. The role of enabling conditions, and processes of resource mobilisation, in institutional entrepreneurship (as identified in literature) were adopted as a central focus of the analysis. This was based on an assumption that to transition towards improved WRE management, institutional entrepreneurship will be necessary to put forward new practices and approaches.

Outcomes of this research objective are intended to support institutional entrepreneurship for improved WRE management by identifying factors which may contribute to the creation of an enabling environment for policy innovation, based stakeholders' past experiences of success.

The following chapter (Chapter 4) has been published in academic literature as the following:

> **Binks, A. N.**, S. J. Kenway, P. A. Lant and B. W. Head (2016). "Understanding household water-related energy use and identifying physical and human characteristics of major end uses." Journal of Cleaner Production **135**: 892-906.

Contributions made to the authorship of the paper are as follows:

Contributor	**Statement of contribution**
Binks, A. N. (Candidate)	Designed analysis (90%) Wrote the paper (90%)
Kenway, S. J.	Designed analysis (5%) Wrote and edited paper (5%)
Lant, P. A.	Designed analysis (5%) Edited paper (5%)
Head, B. W.	Review of theory and methodology

4. Understanding household water-related energy use and identifying physical and human characteristics of major end uses

4.1. Introduction

Energy use associated with water end use is far more significant than that for the delivery of water and wastewater services (Kenway et al. 2008, Kenway et al. 2011b, Rothausen and Conway 2011). In Australia, for example, energy use for residential hot water is estimated to be between 5 (Adelaide) and 11 (Melbourne) times that required to deliver urban water services (Kenway et al. 2008). On average, it is estimated that residential end use of water is responsible for approximately 30% of energy used throughout the urban water cycle (Kenway et al. 2011c), and energy for water heating represents approximately 23% of total Australian residential energy consumption (Commonwealth of Australia 2008a).

This research aims to understand whether total water-related energy use varies significantly between seven different households, and to identify end-use characteristics responsible for greatest variation. Households and their component fixtures (permanently attached components such as a hot water system, or pipework), fittings (removable items such as shower heads, or light bulbs) and appliances are subject to a range of environmental policies and regulations targeting efficient water and energy end use. The potential for energy demand management through water efficiency measures has been recognised (Beal et al. 2012). If we are to maximise the advantages of synergies between water and energy management approaches, data are needed to ensure that our efforts are targeted in the right area and through the most effective pathways. Without an understanding of water-energy interactions, there is also a real risk that attempts to increase efficiency on one side of the linkage (e.g. water) will decrease efficiency of the other (e.g. energy and/or greenhouse gas emissions (GHG)) and lead to unintended consequences. (For an example of this, see (Kenway et al. 2013c)). Current water- and energy-efficiency standards and codes are hard-wired into new residential developments (Beal et al. 2012). As population growth and urbanisation accelerate (e.g. the percentage of world population in urban areas is project to grow from 30% in 1950 to 66% in 2050, (United Nations 2014)), in the absence of clear data and foundational knowledge on water and energy end-use interactions, cities may be at risk of unwittingly increasing their resource use intensity despite best efforts to the contrary. An understanding of influential end-use characteristics and their contribution to variation in water-related energy (WRE) use across households, is a significant knowledge gap for evidence-based policy and program development for water-related energy management (Head 2013). Such an evidence base is needed to enable sustainable resource policy development to target areas with the greatest potential for effective change (Newton and Meyer 2012). In the absence of data, the extent to which policy interventions can be effective in managing water-related energy use is unclear, and resource managers risk problem-shifting between the water and energy spheres (Kenway et al. 2011c).

4.2. Background

The urban water-energy system can be described in terms of both 'human' attributes (e.g. behaviours, rules, economics, governance) and 'physical' attributes (e.g. technologies, fittings, structures, environmental factors, infrastructure issues). These exist at varied scales, from micro (individual end use) to macro (institutional) scales, with a high degree of interaction. Combined, these attributes describe the way we manage and use water and energy. Knowledge of these factors, and their interactions and effect on water-related energy use, is an important foundation for the design of integrated management measures.

The influences of human habits and behaviours on household water and energy use have been noted in qualitative literature (Strengers 2011b, Strengers and Maller 2012, Martinez-Espineira et al. 2014, Fielding and Head 2012, Beal et al. 2013, Gilg et al. 2005, Kurz et al. 2005, Hansen 1996, Jeong et al. 2014). Similarly, the impacts of physical characteristics of households have been assessed, with a focus on key individual components such as hot water system design and efficiency (Kar and Kar 1996, Parker 2003, Boait et al. 2012, Hernandez and Kenny 2012, Bohm 2013, Lai et al. 2014). However, few studies consider the potential for water-related energy management across multiple end uses within a household, or consider both human and physical characteristics of these end uses.

Table 6 provides a summary of literature focused on quantification of water-related energy use in households, summarised according to the impacts assessed, the human and physical characteristics of households considered, and the scale or resolution of results. Most quantitative water-related energy studies assess either total household water or hot water use (Parker 2003, Zhou et al. 2013, Nasrabadi et al. 2013, Vieira et al. 2014, Shimoda et al. 2010, Kuusk et al. 2014), or a single end use (e.g. showers, (Slys and Kordana 2014, Giglio et al. 2014)). Studies which include some consideration of human as well as physical factors included consideration of the effect of varied occupancy on optimal hot water system design (Parker 2003, Shimoda et al. 2010) and domestic hot water consumption (Kuusk et al. 2014), and the impact of shower duration on the cost-effectiveness of a heat recovery unit (Slys and Kordana 2014). Vieira et al. (2014) demonstrate that energy tariffs impact upon optimal energy and service performance for residential hot water systems. Giglio et al. (2014) further consider human factors in detail through economic clustering analysis to assess impact of solar hot water systems on energy savings, finding that human factors significantly influence effectiveness. This concurs with work by Kenway et al. (2013c), who demonstrate that physical management measures alone resulted in less than 15% reduction in household water-related GHG emissions and energy consumption[3], whereas combined physical and behavioural measures had the potential to achieve 85% (GHG emissions) and 93% (energy) respectively.

Only two studies were found to assess multiple end uses (Beal et al. 2012, Kenway et al. 2013c). Kenway et al. (2013c) contribute a validated model of the energy effect of water for each individual end use within a household. The first principles ‘ResWE’ (Residential Water-Energy) model estimates water use based on fundamental parameters such as the flow-rate, duration and frequency of showering. Heat energy is then estimated based on thermodynamics of heating water from one temperature to another, rather than, for example, using energy estimates based on “standard” appliance efficiencies. These allow estimation of water flows, which in turn drive thermodynamic relationships based on water supply and end use temperatures, operational energy requirements, heat transfer coefficients, hot water pipe lengths and stand times, and energy conversion efficiencies, allowing prediction of energy use associated with each water end use. Beal et al. (2012) also assess energy demands for individual water end uses (showers, taps, clothes washers, and dishwashers), based on empirical data for average water end use and technology choice (hot water systems and washing machines). While contributing a valuable assessment of hot water energy demands, the study does not enable insight into non-technological management levers such as the impact of occupancy, behaviour, environment, or structural aspects of the household. Beal et al’s work also focused on energy demand for hot water use, and does not include assessment of the energy conversion efficiency of different hot water heating systems.

[3] excluding a switch to a solar hot water system

Of the studies reviewed, none considered both human and physical influences on individual water-related energy end uses across more than one household. This study aims to provide further insight into Beal et al. (2012) and Kenway et al's (2013c) findings by quantifying variation in water-related energy use across multiple households, and considering both human and physical characteristics which contribute to this variation.

Table 6: Quantitative research assessing the potential for water-related energy management

Author	Impact considered	Household Characteristics		Resolution
		Physical variable	Human variable	
Zhou et al. (2013)	Water supply system energy savings through residential water demand management	NA	NA	Total residential sector water end use. City scale. Theoretical model.
Beal et al. (2012)	Household water-related energy use and GHG emissions reductions through resource efficient stock	Resource efficient stock	NA	Showers, clothes washers, dishwashers, taps. Hot water system type. City scale. Empirical water use data, theoretical energy use model.
Nasrabadi et al. (2013)	Water supply energy savings through residential water demand management	Fittings (supply-side)	NA	Water – individual end use Energy – total residential sector (supply side). City scale. Theoretical model.
Vieira et al. (2014)	Hot water system characteristics impact on grid electricity use, and level of service	Hot water system technology, storage size, clothes washer hot water connection	Electricity tariff	Total hot water use. Household scale. Empirical water use data, theoretical energy use model.

Author	Impact considered	Household Characteristics		Resolution
		Physical variable	**Human variable**	
Parker (2003)	Potential for electrical load demand control	Hot water system design	Occupancy	Total hot water use. City scale. Theoretical model.
Shimoda et al. (2010)	Energy, GHG emissions, and cost reductions through choice of hot water system type	Hot water system design, structure size, structure type (attach/detach), water use	Occupancy	Total household hot water demand. City scale. Theoretical model.
Slys and Kordana (2014)	Financial benefits of installation of shower heat recovery unit	Shower heat recovery unit design, water flow rate	Duration of showers	Shower energy use and costs. Household scale. Theoretical model.
Kuusk et al. (2014)	Cost effectiveness of energy efficiency improvements in apartment buildings	Building size and material thermal properties	Occupancy	Total hot water use. Building (multi-apartment) scale. Empirical water use data, theoretical energy use model.
Giglio et al. (2014)	Electricity savings from installation of solar hot water system	Hot water system type	Family composition and characteristics, socio-economic status, hot water consumption related habits, user satisfaction with technology	Total household electricity cost savings. Suburb scale. Empirical case study.
Kenway et al. (2013c)	Household water-related energy use, costs and GHG emissions	Fittings, fixtures, appliances, hot water system type, temperatures, structural aspects	Occupancy, duration of use, frequency of use, user settings (e.g. temperature of use)	Individual end use (all). Single household. Empirical and model.

4.3. Methods

4.3.1. The Water-Energy-Carbon Links in Households and Cities project

This paper has been conducted as a component of a larger research effort undertaken collaboratively between The University of Queensland (Australia) and the Melbourne water sector and related State agencies. The overarching project has four principal goals: (i) understand water and energy connections in individual households, (ii) characterise “household types”, (iii) understand city-scale water-related energy use and greenhouse gas emissions, and finally (iv) identify opportunities to manage water-related energy use. This will include quantification of the water and greenhouse gas reduction potential of a range of management options including technological, behavioural and policy changes.

This paper reports upon work towards goal (i) outlined above, aiming to understand water and energy connections in individual households. Outcomes of this work will inform the definition of “household types” for water-related energy use and underpin subsequent city-scale analysis.

4.3.2. Approach

This study extends Kenway et al’s detailed analysis of water-energy linkages for a single household (Kenway et al. 2013c). Kenway et al. (2013c) developed a mathematical material flow analysis model, ResWE, to study the interconnections between household water and energy use. The model was applied and validated for a single household in Queensland, Australia (Kenway et al. 2013c). A conceptual diagram of the ResWE model and its components is provided in Figure 3.

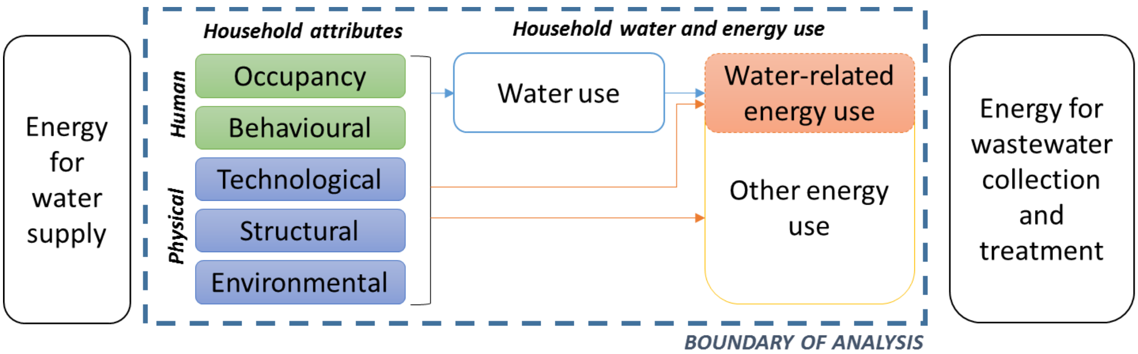

Figure 3: Conceptual diagram of household water-related energy use components in Residential Water Energy (ResWE) model

This paper describes the application of the validated ResWE model to quantify water-related energy use for seven Australian households. The work aimed to explore the impacts of differences between individual households on water-related energy use, costs and GHG emissions. Specifically, we explore here the following questions: (a) How consistent is the magnitude of WRE use, and associated utility costs and GHG emissions, in different individual households? (b) How consistent are the key household characteristics which drive this variation (i.e. individual end uses, and the human and physical characteristics describing their water and energy use)? (c) What implications do these key characteristics have for integrated management of household water and related energy use, costs and GHG emissions?

4.3.3. Scope

In this study, analysis of water-related energy use is restricted to energy use associated with the end use of water within a household. Energy use associated with water supply is not considered here, nor is the energy demand of wastewater collection and treatment processes (see 'Boundary of Analysis' indicated in Figure 3). These areas were excluded because they are the subject of many other analyses, and are also typically small in comparison to water-related energy within households (Kenway et al. 2008, Cook et al. 2012, Arpke and Hutzler 2006, Cheng 2002).

This study also does not consider the determinants of physical and human characteristics within households, such as social or environmental factors external to the household which determine behaviours and technology choices. Analysis is confined to defining physical and human characteristics as they exist in seven real households, and studying the impact of these characteristics on water and energy flows.

4.3.4. Methodology

An overview of the data collection and material flow modelling methodology is provided in Figure 4.

The methodology adopted involved development of a detailed empirical dataset describing the water and energy use characteristics of seven individual households (five in Melbourne, and two in Brisbane; Australia). This detailed dataset for each household included definition of the structural, environmental, behavioural, occupancy and technological characteristics for each water and energy end use, in addition to water and energy supply details (see Section 4.3.5 for detailed description). This dataset was used to create input parameters for a validated mathematical material flow analysis model, 'ResWE' (the Residential Water Energy model), published by Kenway et al. (2013c).

The ResWE model was then applied to analyse water-energy-carbon-cost links for individual household end-use subsystems. Model outputs include the water use, energy use, water and energy costs, and GHG emissions associated with each individual end use, including quantification of the energy use driven by water use (WRE use). Total water use estimated by the model was compared to empirical water use from billing records for each household.

Water-related energy use was quantified across all seven households. This was followed by detailed end use analysis for the five Melbourne households.

The method is further described in the following sections of this paper.

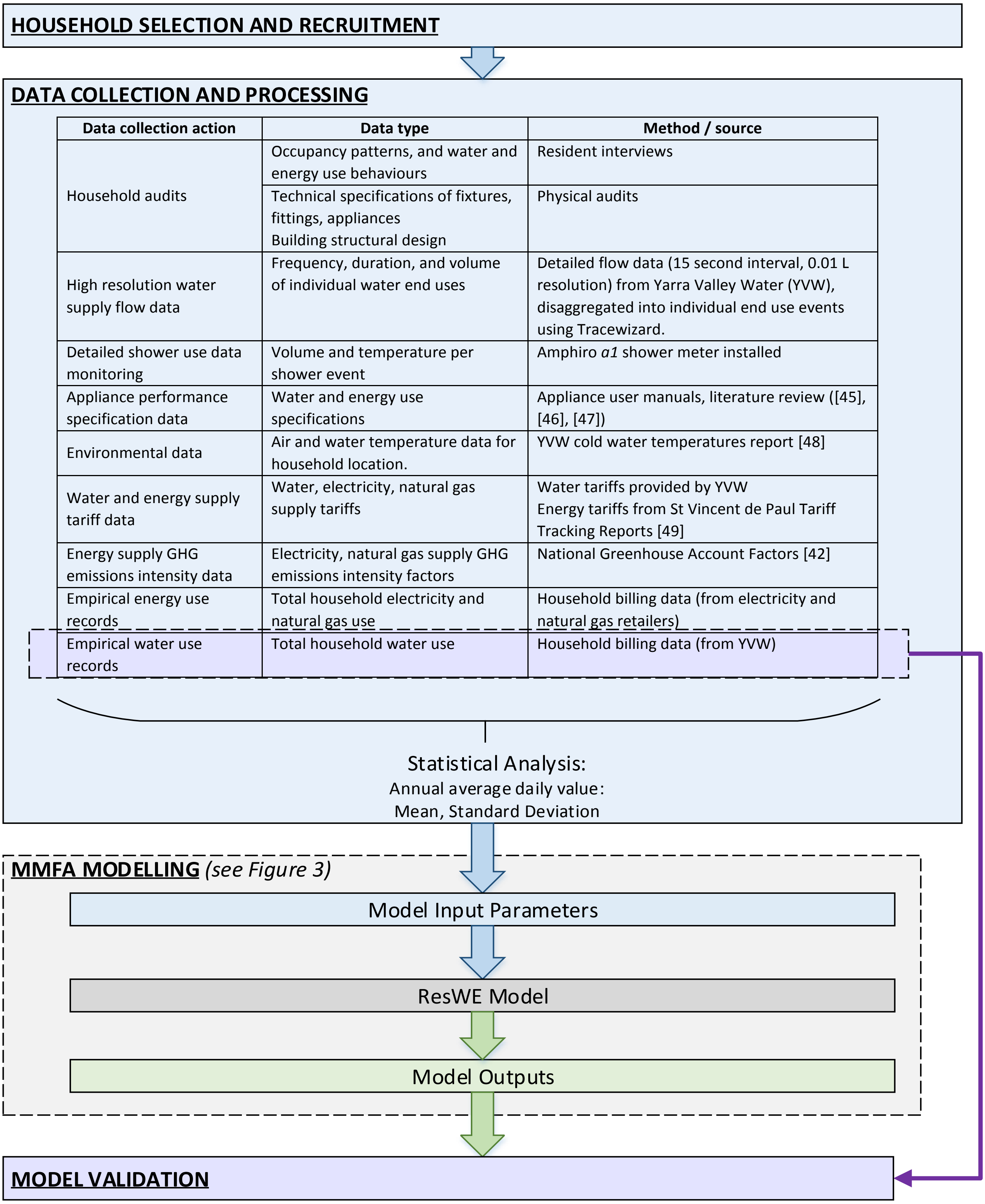

Figure 4: Modelling Process

4.3.5. MMFA modelling

A conceptual diagram of the ResWE model is provided in Figure 5. Kenway et al. (2013c) describe model development in detail, and an overview of the model structure and function is provided below.

The ResWE model (Kenway et al. 2013c) was constructed to understand energy use influenced by water use in households. ResWE applies a demand-driven approach in which specific demands of hot and cold water for ten household subsystems (‘service’ subsystems) are the foundation of the model. These ‘service’ subsystems are: shower, bath, clothes washer, indoor taps, dishwasher, outdoor, toilet, kettle, air-conditioner, and other (non water-related energy use such as heating, cooking, and miscellaneous appliances). The ‘other’ subsystem is included to allow complete accounting of total water and energy use in the household.

Major flows of cold water, hot water and energy for each subsystem are identified using a set of demand equations (described in section 4.3.5.1 below). Energy losses from hot water storage, hot water pipes, and hot water system energy conversion efficiency losses are also identified using a set of loss equations (described in section 4.3.5.2). Water and energy supplied to the household is identified as the sum of subsystem demands (and energy losses), according to a set of supply equations (section 4.3.5.3). The costs for water and energy supply, and the GHG emissions associated with energy supplies, are also accounted for (equations described in sections 4.3.5.4 and 4.3.5.5).

As water-related energy use is the focus of this research, data collection and parameter characterisation focused on accuracy in end use parameters for water subsystems (and their associated energy use parameters). ‘Other’ energy end uses, such as cooking and heating, were not assessed in detail and are not presented in this study.

4.3.5.1. Demand equations

Water and energy demands for each subsystem are calculated using a mathematical material flow analysis, based on model input parameters describing occupancy, behavioural (e.g. frequency of use, temperature of use), technological (e.g. flow rate), structural (e.g. heat transfer coefficient of pipe material), and environmental (e.g. cold water supply temperature) characteristics of the household. Demand equations can be described as follows:

- **Water demand equations**: The water demand to provide the service required for each subsystem is a function of the parameters describing the amount of water used per day per person or household. E.g. for showers, *water demand* [L person^{-1} day^{-1}] = *frequency* [showers person^{-1} day^{-1}] × *duration* [mins shower^{-1}] × *flow rate* [Litres min^{-1}]).
- **Energy demand equations**: The energy demand corresponding to the water demand is calculated using a simple calometric equation for water, as a function of the amount

of water used, the temperature of the cold water supply, and the temperature of the end use. (E.g. *Hot water energy* [kWh hh^{-1} day^{-1}] = *water demand* [Litres day^{-1}] × *calorific value of water* [KJ Litre^{-1} °C^{-1}] × *difference between supply temperature and end use temperature* [°C]).

4.3.5.2. Loss equations

Water-related energy losses throughout the household are also calculated. These include heat transfer to atmosphere from the hot water storage, through hot water pipes, and losses through energy conversion efficiency (the energy lost during conversion of an energy source to heat energy at the hot water system). Losses are calculated using physical equations relating temperatures, heat transfer characteristics, and efficiencies. For example:

- *Hot water storage energy loss* [kWh household^{-1} day^{-1}] = (*surface area of storage* [m^2]) × (*heat transfer coefficient of storage material* [kW m^{-2} °C^{-1}] × (*hot water temperature* [°C] – *ambient air temperature* [°C]) × 24 [hours])
- *Energy conversion efficiency loss* [kWh household^{-1} day^{-1}] = ∑ (*energy demand for all hot water subsystems* [kWh household^{-1} day^{-1}]) × (*energy conversion efficiency factor*)).

4.3.5.3. Supply equations

The service subsystems are supplied with water and energy from ‘supply’ subsystems (including electricity supplies, natural gas supplies and/or solar thermal sources). The supply of water and energy is exactly the sum of the demands by the individual subsystems, as follows:

- ***Water supply*** [L household^{-1} day^{-1}] = ∑ (*water demand for each subsystem*) [L household^{-1} day^{-1}];
- ***Energy supply*** [kWh household^{-1} day^{-1}] = ∑ (*energy demand for each subsystem*, *pipe losses*, *storage losses*, *energy conversion efficiency losses*) [kWh household^{-1} day^{-1}].

4.3.5.4. Water and energy cost equations

The costs to the household for the supply of water, electricity, and natural gas are calculated based on the volumes of water and energy supplied (determined by the supply equations), and a supply tariff structure. Supply tariffs are expressed in terms of ‘fixed cost’ (fixed daily charge by the supplier for a connection), and ‘variable’ cost (the cost associated with the supply of each unit (Litres, kWh or MJ) of water, electricity or natural gas). For example:

- *Water supply cost* [\$ household^{-1} day^{-1}] = *fixed cost* [\$ household day^{-1}] + (*water supply* [Litres household^{-1} day^{-1}] × *variable cost* [\$ Litre^{-1}]).

4.3.5.5. Energy supply GHG emissions equations

The greenhouse gas emissions (GHG) associated with electricity and natural gas supplied to the household are calculated, based on the volume of energy supplied (determined by the supply equations), and a GHG emissions intensity factor for electricity or natural gas supply. For example:

- *Electricity GHG emissions* [kgCO_2-e household^{-1} day^{-1}] = *electricity supply* [kWh household^{-1} day^{-1}] × *electricity supply emissions intensity factor* [kgCO_2-e kWh^{-1}].

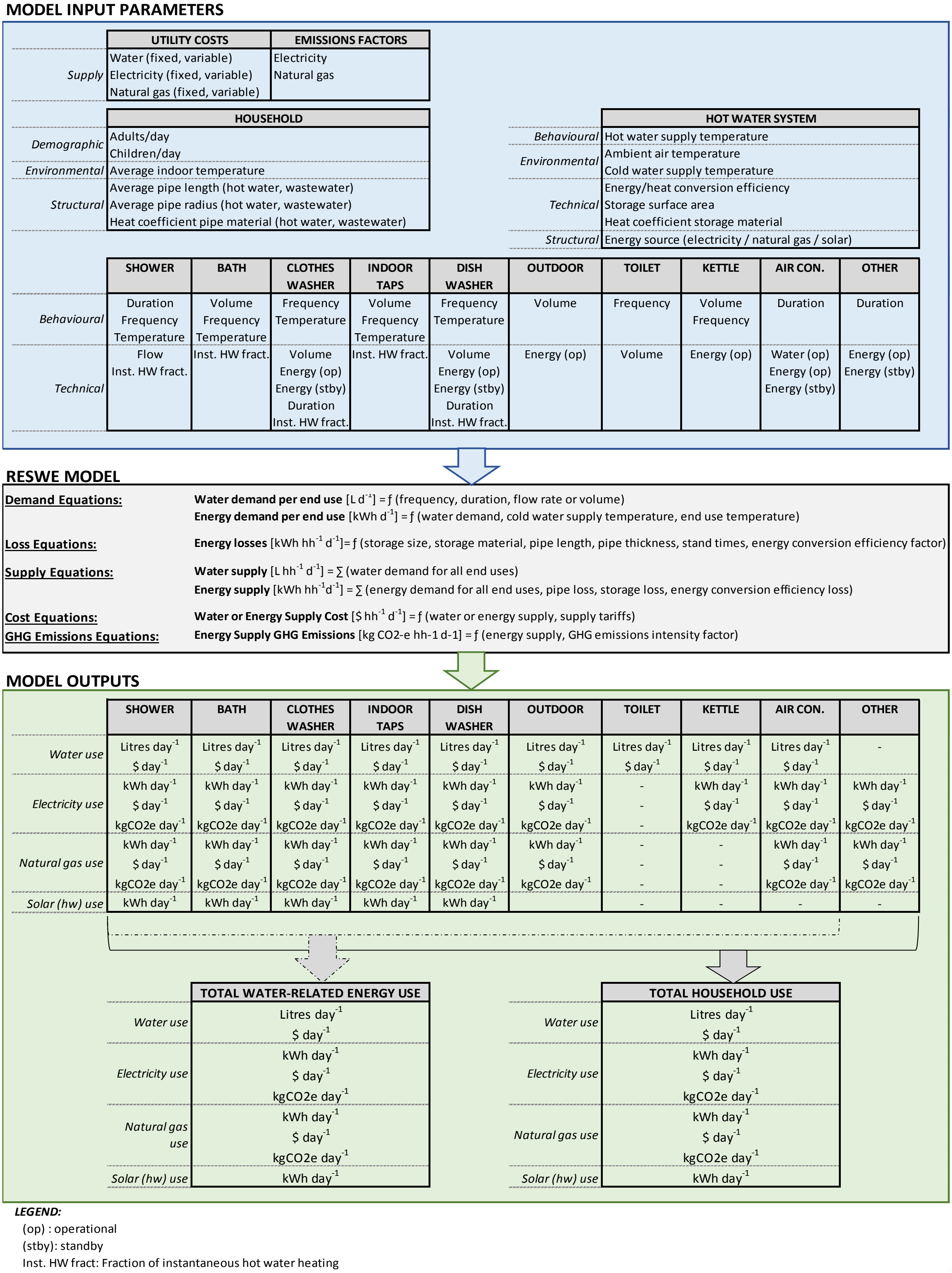

Figure 5: Conceptual diagram of ResWE MMFA model

4.3.6. Household selection and recruitment

Households were recruited in Melbourne (Victoria) and Brisbane (Queensland) in Australia, to provide environmental contrast for total water and related energy use between Victorian and Queensland conditions. Melbourne is situated in the south-eastern state of Victoria, and has a temperate oceanic climate (Tapper 1996). Brisbane is the capital city of Queensland in the north-east of Australia, in the humid sub-tropical climate zone (Tapper 1996). Melbourne experiences significant climate variability, compared to the more stable conditions in Brisbane. A summary of climate statistics for the two cities is provided in Table 7.

Table 7: Summary of climate conditions for Brisbane and Melbourne

	Average Temperature (°C)					
	Summer Max	Summer Min	Winter Max	Winter Min	Annual Max	Annual Min
Melbourne (Victoria) (Australian Government Bureau of Meteorology 2015b)	25.9	13.0	13.5	6.0	19.9	10.2
Brisbane (Queensland) (Australian Government Bureau of Meteorology 2015a)	30.2	20.3	23.2	10.1	26.5	16.3

The ResWE model requires significant detail for each household describing occupancy, behavioural, technological, structural and environmental characteristics. Empirical data was collected to capture conditions in each household, through physical audits, interviews and analysis of water meter data. Criteria governing household selection therefore focused on access to data, and potential for repeat visits to confirm parameters.

Five Melbourne households were selected for the study with the assistance of the industry research partner Yarra Valley Water (the water utility for the northern and eastern suburbs of Melbourne, in the state of Victoria, Australia). Selection of households drew from a pool of Yarra Valley Water employees engaged in a concurrent water use study, in order to take advantage of the detailed water use dataset (see below for further detail). Additional benefits of drawing on households from within the pool of Yarra Valley Water employees included greater understanding and willingness to participate in intrusive data collection procedures, and the longer-term availability of participants for further data collection where necessary.

For Melbourne households, data collection focused on a period of one year, from April 2012 until March 2013. Households were screened for study eligibility according to the following criteria:

- No solar PV installed – Households with solar PV installed were only able to provide historical data for net energy use (energy imported when use exceeded generation through solar PV).
- Stable occupancy for approximately 5 preceding years – Households with a history of stable occupancy were assumed to have more consistent patterns of water and energy use, allowing greater confidence in model parameter development.

Two Brisbane households were also modelled for the study. These households were selected from within the research team, due to similar willingness to participate and ongoing availability for data collection.

4.3.6.1. Benchmarked water use of participant households

Given the great diversity of households generally, we did not seek to be representative in the selection of households, rather we sought to characterise a diversity of household types and systems. With regard to total household water use we compared each of the five Melbourne participant households (HH1 – HH5) with water use for urban households in Melbourne. The households were benchmarked against annual water use for the 2011 calendar year for 1175 households in the Yarra Valley Water (YVW) service area, using data from a study into household appliance stock and usage patterns (Roberts 2012). This demonstrates that HH3 and HH5 are on the end of conservative water users in the area, falling in the 2^{nd} quartile of water users in the study sample. HH4 can be considered an average water user, falling close to the median in the 3^{rd} quartile of water users, and HH1 and HH2 high water users falling above the 4^{th} quartile for the study sample. Results of the comparison indicate that Melbourne participant households are distributed across the spectrum of water use in their service area, and therefore capture a range of water use conditions.

Table 8: Water use statistics for sample of 1175 Yarra Valley Water households, 2011 (data from Roberts (2012))

Statistic	**Sample size** (hh)	**Mean** (L hh^{-1} day^{-1})	**Standard deviation** (L hh^{-1} day^{-1})	**Q1** (L hh^{-1} day^{-1})	**Median** (L hh^{-1} day^{-1})	**Q3** (L hh^{-1} day^{-1})
Melbourne	1,175	392	230	244	356	483

Brisbane households (HH6 and HH7) were compared to average household water use data for Brisbane from the South East Queensland Residential End Use Study (SEQREUS, (Beal and Stewart 2011)). Average water use for Brisbane households was reported to be between 331 L hh^{-1} day^{-1} (winter 2010) and 347 L hh^{-1} day^{-1} (summer 2010-11). Both Brisbane households studied (HH6 and HH7) can be considered to be above average water users.

4.3.7. Data collection and processing

A structured survey was used to collect detailed data on household water and energy use characteristics. The survey included a questionnaire for residents relating to occupancy rates and end use behaviours, in addition to a detailed physical audit of appliances, fixtures, fittings, and structural characteristics of the household. This data was used to define mean and standard deviation values for model input parameters.

For behavioural and technical parameters, additional detailed data was sought to increase the accuracy of the household survey data. This was only possible for some households, due to constraints in data format and compatibility of monitoring technologies with household equipment. Consequently, data sources for some behavioural and technical parameters vary between households. Additional detailed data sources were used in the following cases:

- HH3 and HH5: High resolution water supply flow data was available for HH3 and HH5. This data was analysed to provide high confidence estimates of duration, frequency, flow rate and volume of use for each water end use within these households.
- HH4 and HH7: Shower monitors (Amphiro *a1*) were installed in eligible households (HH4 and HH7) to provide improved estimates of shower temperature, volume and usage data, as shower use data were recognised to be particularly influential for household water-related energy use (Kenway et al. 2013c).

Occupancy, structural and environmental parameters were derived using a uniform approach across all households.

Appliance performance specification data, environmental data (air and water temperatures), supply tariff data (for water, electricity, and natural gas supply) and GHG emissions intensity data (GHG emissions factors for electricity and natural gas supplies in Victoria) were also collected and used for parameter characterisation (see Supplementary Information 1 for detailed methodology).

An overview of data collection and processing methods is provided in Table 9.

Table 9: Overview of data collection and processing methods

Parameter Type	Mean	Standard Deviation
Occupancy	Interview based on resident weekly patterns, absences, and guests during study period	Standard deviation of number of occupants per day over 365 day sample, based on interview responses
Behavioural	(a) Interview based on resident weekly patterns (b) Statistical analysis of high resolution water supply flow data (HH3 and HH5) (c) Statistical analysis of Amphiro a1 shower monitor data (HH4 and HH7)	(a) Interview data: Standard deviation based on estimates of weekday and weekend behaviour for summer and winter (b) High resolution water supply flow data (HH3 and HH5): statistical analysis (c) Amphiro a1 shower monitor data: statistical analysis
Technological	(a) Appliances: Technical data from user manual, or if not available, from literature for similar make / model / age / rating (b) Fittings/fixtures: Empirical measurements taken during household audit, based on average operating condition demonstrated by resident (c) Statistical analysis of high resolution water supply flow data (HH3 and HH5)	(a) and (b): Empirical data and user manual/literature: Standard deviation based on data confidence (25/50/100%) (c) High resolution water supply flow data (HH3 and HH5): statistical analysis

Parameter Type	Mean	Standard Deviation
Structural	Observation of material type, and physical measurements of lengths, diameters, and volumes taken during household audit. Thermodynamic properties of materials taken from literature.	Fixed, no standard deviation
Environmental	(a) Air temperature data: Statistical analysis of ABS data (b) Cold water temperature data: Statistical analysis of network temperature data provided by Yarra Valley Water	(a) Air temperature data: Statistical analysis of ABS data (b) Cold water temperature data: Statistical analysis of network temperature data provided by Yarra Valley Water

Empirical total water, electricity and natural gas records were collected from water and energy retailers for comparison with model outcomes, with empirical water data in particular used to compare model performance to historical usage during the study period.

Key assumptions for water and energy supply tariffs and GHG emissions factors are presented in Table 10 and Table 11.

Table 10: Supply tariffs adopted - water, electricity and natural gas

	Water		**Electricity**		**Natural Gas**	
	Fixed ($AU y^{-1})	**Variable** ($AU L^{-1})	**Fixed** ($AU y^{-1})	**Variable** ($AU kWh^{-1})	**Fixed** ($AU y^{-1})	**Variable** ($AU kWh^{-1})
Tariff	441.76	0.0037	341.28	0.2678	215.68	0.0625

Table 11: GHG emissions factors adopted - electricity and natural gas (Victoria)

Energy Source	**GHG Emissions Intensity** **(kg CO_2-e kWh^{-1})**	**Data Source**
Electricity	1.17	Indirect (scope 2) emissions factor for the consumption of purchased electricity from the grid, value for Victoria, Table 5 (Commonwealth of Australia 2013).
Natural Gas	0.18432	Emission factor for the consumption of natural gas distributed in a pipeline, Table 2 (Commonwealth of Australia 2013).

4.4. **Results**

4.4.1. Model parameter set

An overview of household characteristics is presented in *Table 12*, and a summary of model input parameters for key water-related energy end uses is provided in Table 13, with the full parameter set included as Supplementary Information 2.

Households varied according to number and age of occupants, hot water system type (solar with gas continuous boost, gas continuous, gas storage, and electric storage), clothes washer type and configuration (front load or top load, hot and cold tap connection or cold connection only), in addition to heating, cooling, cooking, and outdoor water use characteristics.

Physical and human end use characteristics varied significantly between households. For example in the case of shower use, frequency varied between 0.9 to 1.8 showers day^{-1}, duration between 4.0 and 11.8 minutes shower^{-1}, flow rate between 4.4 and 11 Litres minute^{-1}, and temperature from 32°C to 45°C.

Table 12: Overview of household characteristics

HH	Occupancy			Hot Water System				Clothes Washer			Heating		Cooling		Cooking		Outdoor Use	
	Adult Residents	Child Residents	Average Occupancy	Solar	Gas Instant	Gas Storage	Electric Storage	Top Load	Front Load	Hot / Cold Tap Connection	Gas	Electric	Evap Cooler	Electrical	Gas	Electric	Rainwater Tank	Irrigation
HH1	4	-	3.65	X	X			X	X	C	Central	-	Central	-	Stove	Oven	No	Hand
HH2	4	-	3.04	X	X				X	H+C	Central	-	Central	-	-	All	No	Drip
HH3	2	2	3.42			X			X	H+C	Central	-	-	Space	Stove	Oven	External	Hand
HH4	2	2	3.95		X			X		H+C	Central	-	Central	-	Stove	Oven	No	Hand
HH5	2	-	1.73		X				X	C	Space	-	-	-	All	-	No	Drip
HH6	4	-	4.01				X		X	C	-	-	-	-	-	All	No	-
HH7	2	2	3.85			X			X	C	Space	Space	-	Space	Stove	Oven	External	-

Table 13: Overview of model input parameters for key water-related energy end uses

End Use	Parameter	Melbourne					Brisbane	
		HH1	HH2	HH3	HH4	HH5	HH6	HH7
Hot water system	Cold water supply temperature (°C)	16.7	16.3	16.3	15.6	16.9	21.3	21.3
	Hot water temperature (°C)	60	60	60	60	60	60	55
	Storage surface area (m^2)	2.8[a]	1.8[a]	1.8	-	-	6.4	3.0
	Average length hot water pipe (m)	8	12	5	15	7	7	7
	Energy conversion efficiency (-)	1.54[b]	1.54[b]	1.31	1.54	1.54	1.02	1.31
Shower	Frequency (showers day^{-1})	1.6	1.8	0.9	0.9	1.4	1.6	1.5
	Duration per shower (min)	10.3	10.0	5.8	6.1	11.8	4.8	4.0
	Flow rate (L min^{-1})	6.0	9.0	4.4	10.5	7.4	8.0	11.0
	Temperature (°C)	40	41	32	38	43	45	41
Clothes Washer	Frequency (cycles day^{-1})	0.4	1.0	1.2	0.4	0.3	0.6	0.9
	Energy use per cycle[c] (kWh $cycle^{-1}$)	1.1	0.8	0.4	0.2	0.4	1.1	0.35
	Water use per cycle (L $cycle^{-1}$)	170	60	33	120	40	80	62
	Cycle temperature (°C)	40	40	30	40	36	21.3	42
Dishwasher	Frequency (cycles day^{-1})	1	0.3	0.5	0.5	0.3	-	1.0
	Energy use per cycle[c] (kWh $cycle^{-1}$)	1.00	1.75	0.25	0.90	0.9	-	0.33
	Water use per cycle (L $cycle^{-1}$)	16	20	9	13	22	-	18
	Cycle temperature (°C)	60	65	65	50	40	-	50
Air Conditioner	Duration of use (min day^{-1})	178	185	6	99	0	-	13
	Water use (L min^{-1})	1.3	0.5	-	1.5	0	-	-
	Energy use (W)	700	900	2334	930	0	-	4500
Kettle	Frequency (boils day^{-1})	-	1.4	2.1	1.4	2.6	1	2
	Volume per event (L $boil^{-1}$)	-	0.8	1.0	1.0	1.0	1.3	1.2

[a] solar hot water storage

[b] continuous gas booster for solar hot water system

[c] excludes energy for water heating

(green) indicates parameters informed by Amphiro a1 shower monitoring

(blue) indicates parameters informed by TraceWizard

4.4.2. Review of model performance

The ResWE results were reviewed against total measured water use collected by the servicing water utilities (Yarra Valley Water and Queensland Urban Utilities).

A comparison of modelled water use with empirical water use from utility data is presented in *Figure 6* (and *Table 14*, 'Modelled Water % Empirical Water Use'). Modelled water use performs well against empirical utility data, with modelled average daily water use (including uncertainty) falling within one standard deviation of average daily values from utility data for all except HH1. Model performance for HH1 overestimates water use.

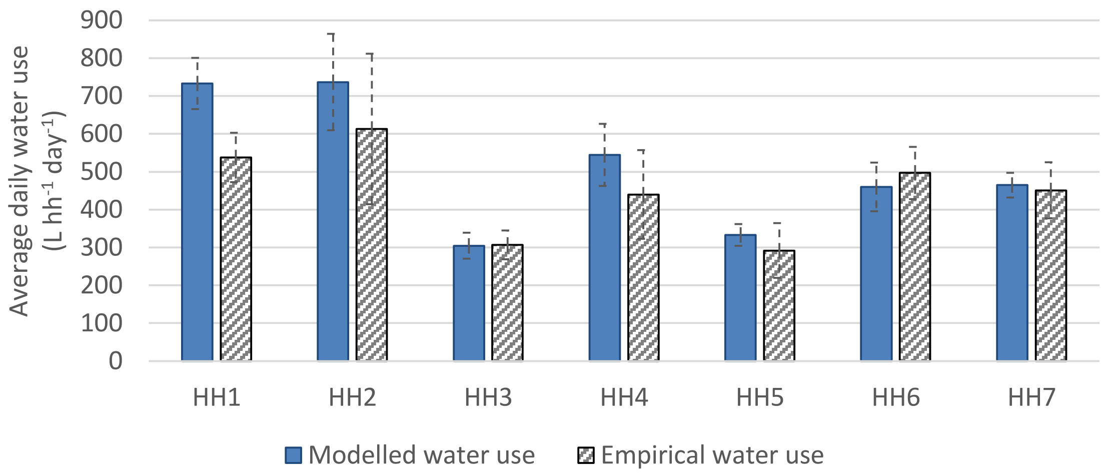

Figure 6: *Modelled water use compared to empirical water use data*

4.4.3. Model outcomes

Model outcomes are summarised in *Table 14*, *Figure 7* and *Figure 8*. Modelled water and water-related energy use, costs and GHG emissions are presented in comparison to empirical total water use and total energy use from billing records, in addition to estimated costs and GHG emissions (calculated based on empirical total energy use, using emissions factors and supply tariffs in *Table 10* and *Table 11*). Detailed data for individual end uses is provided as Supplementary Information 3.

Melbourne households (HH1 to HH5) were the focus of detailed analysis, with Brisbane households (HH6 and HH7) included for geographic contrast in total water and related energy use. Water and energy supply costs, GHG emissions and detailed end use analysis are not presented for Brisbane households (HH6 and HH7).

4.4.3.1. Water-related energy use

Water-related energy use in the households studied ranges from 7 to 21 kWh hh^{-1} d^{-1} (*Table 14*; or 2 to 7 kWh $person^{-1}$ d^{-1} *Figure 8*c). Studies by Kenway et al. (2013c) and Beal et al. (2012) estimate water-related energy use to be an average of 2.9 to 4.4 kWh $person^{-1}$ d^{-1} respectively. While results of this research support these estimates as a reasonable average, they also demonstrate that the potential for variation between different households is significant.

The two Brisbane households in the study (HH6 and HH7) show a markedly higher percentage of water-related energy use (76% and 79%, *Table 14*) than the Melbourne households (13% to 24%), due to lower or absent space heating requirements for the warmer Brisbane climate and warmer water supply temperatures.

Table 14 Overview of average daily household water and related energy use

			Melbourne					Brisbane	
			HH1	**HH2**	**HH3**	**HH4**	**HH5**	**HH6**	**HH7**
Water use	Total Water Use[1]	(L hh^{-1} d^{-1})	540	610	310	440	292	497	451
	Total Energy Use[2]	(kWh hh^{-1} d^{-1})	70	164	52	100	49	17	19
Energy use	WRE Use	(kWh hh^{-1} d^{-1})	16	21	7	15	12	13	15
	WRE % Total Energy		**23%**	**13%**	**13%**	**15%**	**24%**	**76%**	**79%**

Notes:

[1]*Based on empirical water billing data*

[2]*Based on empirical electricity and natural gas billing data, using supply tariffs and GHG emissions factors in Table 10 and Table 11*

4.4.3.2. Water and related costs and greenhouse gas emissions

Water and related energy costs for the Melbourne households range between \$3.52 to \$5.78 hh^{-1} d^{-1} (*Table 15*). Of the variable portion of utility costs, those associated with water and related energy use represent approximately 23%-55% of total variable water and energy costs for the households, dominated by water costs (*Figure 7*c).

Table 15 Overview of average daily household water and related energy use costs and greenhouse gas emissions

			HH1	HH2	HH3	HH4	HH5
Water and energy supply costs	Total Supply Costs[1,2]	(\$ hh^{-1} d^{-1})	\$12.24	\$19.13	\$9.53	\$14.05	\$8.47
	WRE Supply Cost	(\$ hh^{-1} d^{-1})	\$5.78	\$5.15	\$3.52	\$5.02	\$3.86
	WRE % Total Costs		**47%**	**27%**	**37%**	**36%**	**46%**
Energy supply GHG emissions	Total Energy GHG[1]	($kgCO_2$-e hh^{-1} d^{-1})	23.2	47.2	21.2	32.2	15.9
	WRE GHG	($kgCO_2$-e hh^{-1} d^{-1})	5.7	3.0	2.9	4.3	3.4
	WRE % Total GHG		**25%**	**6%**	**14%**	**13%**	**21%**

Notes:

[1]*Based on empirical electricity and natural gas billing data, using supply tariffs and GHG emissions factors in Table 10 and Table 11*

[2]*Includes modelled water costs, with empirical natural gas and electricity costs from billing data*

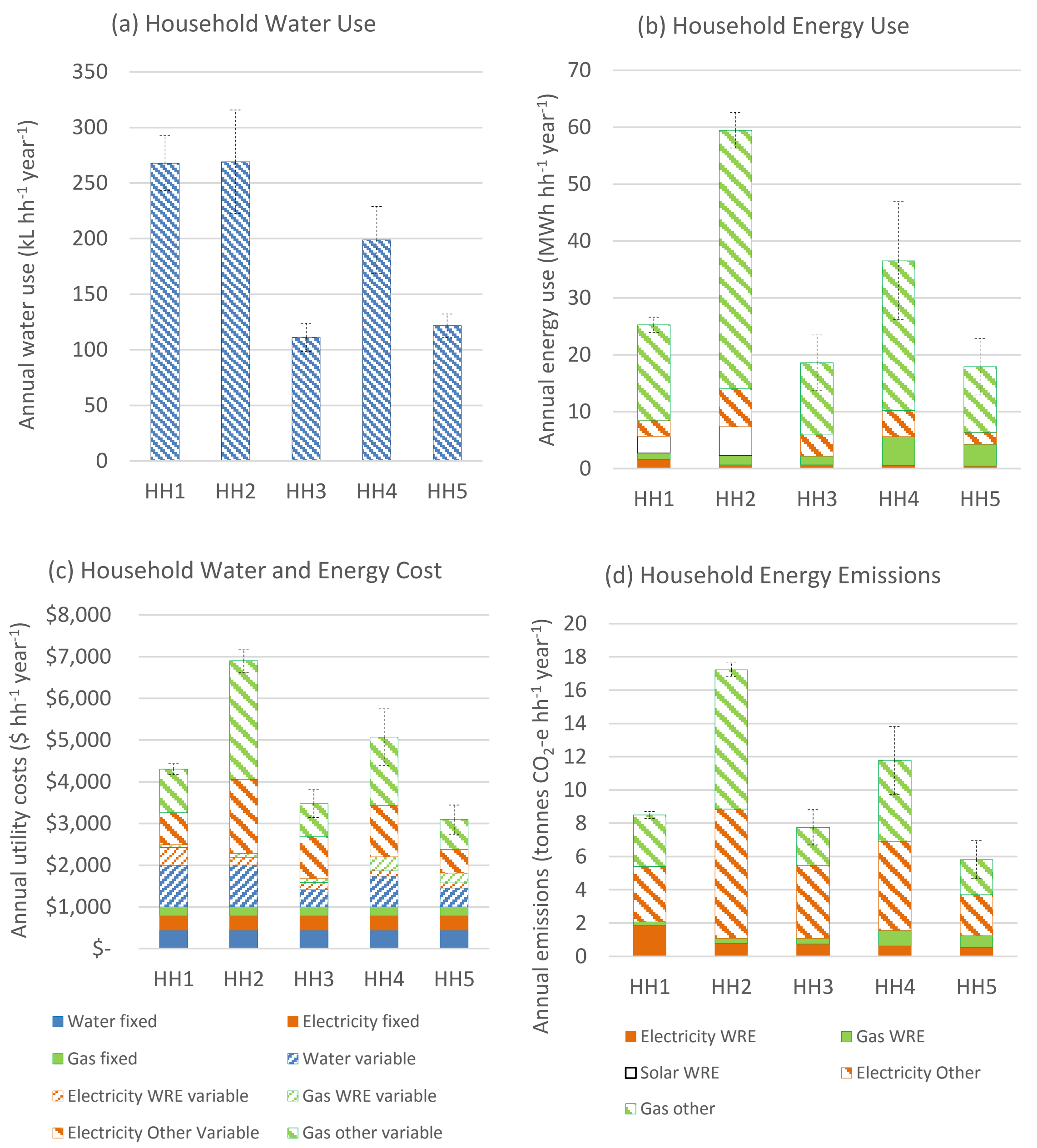

Figure 7: *Overview of household energy use, GHG emissions and utility costs*

In the Melbourne households studied (HH1-HH5) GHG emissions associated with water-related energy use range between 2.9 to 5.7 $kgCO_2$-e hh^{-1} d^{-1} (*Table 15*) or 1 to 2 tonnes CO_2-e hh^{-1} yr^{-1}, comprising 6% to 25% of total household energy-related GHG emissions (*Table 15* and *Figure 7*d).

Water use, energy use, costs and GHG emissions show a consistent pattern across the five Melbourne households (*Figure 7*a-d), with higher water users also higher energy users and vice versa. The exception to this is water use in HH1, due to lower other (i.e. non-water related) energy use and high water use for showers and evaporative cooling (see *Figure 8*b).

Water use varies markedly between 90 and 240 L $person^{-1}$ d^{-1} (*Figure 8*a), driven primarily by showering and evaporative cooler use (*Figure 8*b). Hot water use represents between 18% and 62% of total water use (*Figure 8*a), and is significantly lower in HH3 (18%) due to conservative shower duration and relatively cool shower temperatures (see Table 13).

Solar hot water use in HH1 and HH2 comprises 50% to 67% of total water-related energy use (*Figure 8*c). Electricity use for water-related energy dominates in HH1, driven by operating energy requirements for dishwashers and clothes washers (*Figure 8*d, and *Table 13*). This contrasts with dominance of water-related natural gas use for HH2 to HH5, driven by gas continuous water heating for shower use. Hot water system losses in HH4 and HH5 are higher than other households (*Figure 8*c), due to lower energy conversion efficiencies for continuous gas hot water systems (*Table 13*).

HH1 and HH2 display higher water-related electricity costs due to clothes washer and dishwasher energy use, whereas HH4 and HH5 display higher water-related natural gas costs due to continuous hot water system conversion efficiency loss (Figure 8e and f). Despite reduced imported energy requirements for HH1 and HH2 due to solar hot water heating, their water and related energy costs are still relatively high. This is due to the cost associated with higher water use for these households, and higher water-related electricity use (through clothes washers and dishwashers). The more water-intensive end uses are more influential end uses in terms of water and related energy costs (Figure 8e and f), as a result of higher proportional fixed costs for water end uses (in contrast to energy fixed costs, which are distributed across all household energy end uses).

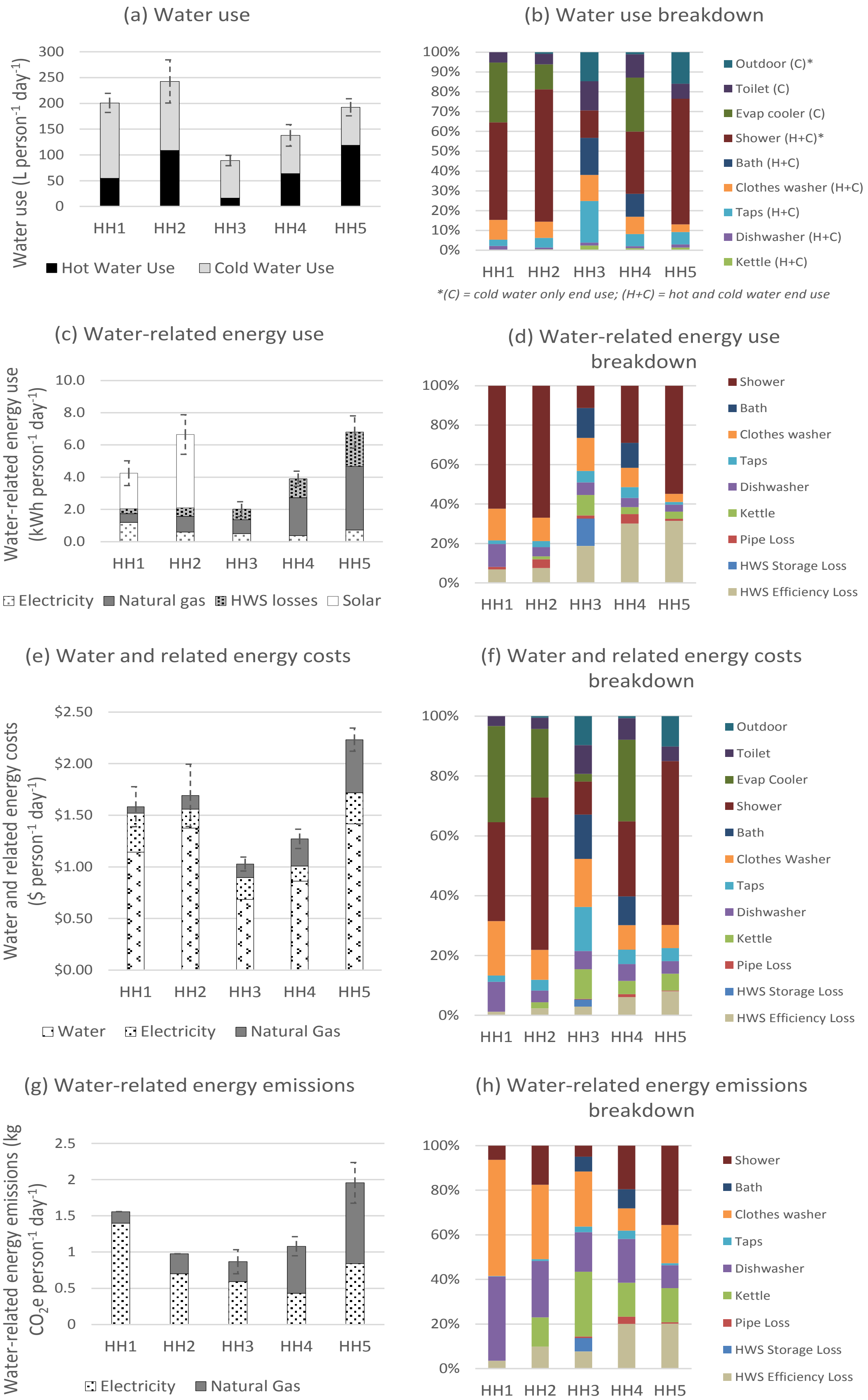

Figure 8: Per person water use and related energy use, costs and GHG emissions (based on household occupancy)

GHG emissions associated with water-related energy use in HH1 and HH2 are still significant (*Figure 8*g), despite a reduced dependence on carbon-based energy as a result of solar thermal hot water supplies. These GHG emissions are driven primarily by operational electricity use for dishwasher and clothes washer use (*Figure 8*h).

Key end uses which contribute to variation in water-related energy use across households are showers (0.2 – 4.7 kWh person^{-1} d^{-1}), energy losses from hot water systems (0.4 – 2.1 kWh person^{-1} d^{-1}), and clothes washers (0.3 – 0.8 kWh person^{-1} d^{-1}) (*Figure 8*d). Literature focused on water-related energy use for these end uses (showers, hot water systems, and clothes washers) is dominated by technical design considerations (Beal et al. 2012, Kar and Kar 1996, Boait et al. 2012, Hernandez and Kenny 2012, Lai et al. 2014, Vieira et al. 2014, Shimoda et al. 2010). The input parameter set for this study, however, demonstrates a high degree of variability in human behavioural characteristics associated with these end uses, particularly for shower use (see Table 13). This is of particular interest for households with solar hot water systems, as model outcomes suggest that despite significantly offset energy demand, water use for showers is still high and contributes significantly to household costs.

Showers are consistently influential across the seven households studied in terms of water use (14% to 67% of total), water-related energy use (11% to 67% of total), water and energy costs (11% to 59% of total), and GHG emissions (5% to 36% of total). Dishwasher use emerges as an influential water-related end use in terms of GHG emissions despite a relatively low contribution to water and water-related energy use (*Figure 8*h). This is due to a higher 100-year impact factor for GHG emissions from electricity supplies in comparison to natural gas water heating (see *Table 11*), and dishwasher reliance on electricity supplies for operation and water heating.

4.5. Discussion

4.5.1. Variability, significance and management of water-related energy use

The significance of water-related energy use (7 to 21 kWh hh^{-1} d^{-1}, comprising 13% to 24% of total household energy use in Melbourne households, 76% to 79% in Brisbane households) and associated variable costs (23% to 53% total variable utility costs in Melbourne) and GHG emissions (6%-25% of total household GHG emissions in Melbourne) highlight the potential for water end use demand management for energy conservation in the households studied. For example, the variation in water-related energy use for showering across the Melbourne households studied (0.8 to 14.1 kWh hh^{-1} d^{-1} or

0.2 to 4.7 kWh person^{-1} d^{-1}, see Supplementary Information 3) suggests that water utility demand management programs (technological and/or behavioural) focused on shower usage could be an effective strategy to manage household energy use, costs and GHG emissions. Similarly, for the households studied, programs targeting dishwasher or clothes washer usage (through behaviour change such as reduced frequency through full loads, or incentives for uptake of water- and energy-efficient appliances) are likely to have a notable impact on household costs and GHG emissions. The growing prevalence of smart metering enhances opportunities to account for the impacts of such measures, and may allow water utilities to demonstrate both the benefits to consumers and to quantify the water cycle energy use and GHG emissions 'offset' through demand management (as a more cost-effective option than supply-side energy initiatives). For example, programs focused on changing end user behaviour through combined water and energy use feedback have been demonstrated to be more effective than those targeting water use alone (Jeong et al. 2014). Furthermore, end use demand management programs focused on households have been shown to save more supply-side energy use (e.g. energy required to treat and deliver water services) than those targeting any other sector (Zhou et al. 2013).

The strong interlinkages between water and energy use highlighted in this paper lend weight to the concept of simultaneous (i.e. coordinated) smart metering of water and energy in households. Benefits of such an approach could include greater dynamic (time-based) resolution of the energy signal associated with water use. For example this could start to characterise, and provide feedback to, different types of shower user or the use of different settings for clothes washing. Integrated metering may also support a step towards integrated end-use service delivery (Knoeri et al. 2015), which advocates understanding, managing, and bringing demand to sustainable levels through the integration of end-users and service demands with infrastructure operation. Knoeri et al. (2015) provide examples of quantitative service measures for UK households which might be used as an intermediate step towards such an approach (see category 'hygiene/cleanliness' for water-related energy end use services).

4.5.2. High water use in households with solar hot water

Both households with solar thermal hot water heating (HH1 and HH2) shower more frequently (1.6 to 1.8 showers person^{-1} d^{-1}, *Table 13*) and for significant duration (10 minutes shower^{-1}). It is very interesting that that these households with solar thermal hot water systems demonstrated high per-capita and total water use, driven primarily by showering. This contrasts with significantly reduced needs for purchased energy for water heating (50% to 67% reduction) for these households, highlighting the potential impact of inconsistencies between water efficiency and energy efficiency messaging. Solar hot water systems are marketed to households on the basis of reduced energy costs and environmental benefits through reduced operational GHG emissions, however without accompanying focus on water-use behaviours and fittings, solar hot water system installation has the potential to lead to increased water consumption in response to a 'solved' hot water problem. In modelling for all five Melbourne households, water costs dominated variable utility costs for water-related end uses (see *Figure 7*c), and consequently the costs associated with any behaviour-driven increase in water use following solar hot water system installation could match or outweigh the costs saved through reduced energy requirements. While the sample size supporting these observations is small (N=5), it may be important that the substantial energy benefits of solar hot water system installation be supported with appropriate water demand management to avoid problem-shifting from energy use to water use. Further analysis with a larger sample size of solar/non-solar households to consider the influence on water use also appears warranted.

4.5.3. Influence of human characteristics significant

The influence of human behavioural characteristics at household level suggests that efficient design of appliances, fittings and fixtures alone is not sufficient to manage water-related energy use, costs and GHG emissions. As discussed above, shower durations in the studied households with solar hot-water systems (HH1 and HH2) are associated with higher water use. Due to higher variable costs for water, total costs for shower use in these households are higher than the combined water and energy costs for gas-heated showers in HH3 and HH4, negating the cost benefits of solar hot water heating. Comparison of dishwasher use in HH1 and HH2 also shows that despite a significantly higher operational energy requirement in HH2 (1.75 kWh $cycle^{-1}$ vs. 1 kWh $cycle^{-1}$), dishwasher energy use in this household is nonetheless lower. This is due to the lower frequency of use in HH2 (0.3 compared to 1 cycle day^{-1} in HH1), leading to half the total water-related energy use, half the combined water and energy cost, one-third the GHG emissions, and lower water use. Human characteristics of households also influence the effectiveness of gas continuous hot water systems, due to the fact that efficiency losses for continuous systems will scale proportional to hot water use. Despite having no losses from storage, per person efficiency losses from gas continuous hot water systems in HH4 and

HH5 (1.2 and 2.1 kWh person^{-1} d^{-1} respectively) were higher than combined efficiency and storage losses from the gas storage hot water system in HH3 (0.3 kWh person^{-1} d^{-1}). Household occupancy, frequency and duration of use will have significant impact on system energy efficiency, and suggest that gas storage hot water systems may be more efficient in higher-occupancy households. These outcomes highlight the need for a focus on both the human characteristics of households and technical design considerations when implementing water-related energy management programs.

4.5.4. Limitations

This study involved analysis of the water-related energy use of a small set of individual households, with the aim of understanding end uses which have most influence on variation between households. The focus of the work was on detailed description of different individual households. The work was not intended to capture all representative household types. Participant households all fall within a narrow socio-demographic range, with similar incomes and education levels. As Melbourne households were selected from within a set of water utility employees, it can be assumed that all participants have a higher awareness of water use issues than the broader Australian population. It is anticipated that these factors affect the water and energy use practices of the participants. Nonetheless, modelling results indicate significant variations emerged in water and energy uses, taking account of fixtures, fittings, technologies, behaviours, and other household attributes within this small sample. Moreover, comparison of water use in the sample households and average Australian household water use demonstrates that the sample captures a broad cross-section of total water use characteristics. It is expected that studies including households with more diverse socio-demographic characteristics may show further variations in water and energy use attributes. Furthermore, all households participating in the study were detached dwellings, whereas multi residential dwellings may be expected to involve different water and energy use characteristics than detached dwellings.

4.6. Conclusions

This study provides detailed quantification of the energy use associated with different water end uses, and provides insight into the potential for variation in influential end-use characteristics between different individual households.

The variation in water-related energy use between the seven households was significant (7 to 21 kWh hh^{-1} d^{-1}, or 2 to 7 kWh person^{-1} d^{-1}). Water-related energy use was also substantial, comprising between 13% and 79% of total household energy use, with higher values observed in Brisbane where space heating in households is considerably lower than Melbourne.

Differences in WRE use between Melbourne households were driven by shower use, hot water system conversion efficiency and storage energy losses, and clothes washer use. For WRE GHG emissions, dishwasher use emerged as influential in addition to showers, hot water system energy losses, and clothes washers. Both human behaviours and physical design characteristics contributed significantly to these differences between households.

Variable water and related energy costs comprised 23-55% of household water and energy costs in Melbourne, and were dominated by water costs. GHG emissions associated with water-related energy use in these households comprised 6%-25% of total household GHG emissions.

This study suggests that further investigation of shower use as a major target for combined water and energy demand management initiatives is warranted. This is due to its substantial and consistent contribution, for all five Melbourne households analysed in detail, to variation in household water use (14% to 67% of total), water-related energy use (11% to 67% of total), costs (11% to 59% of total) and GHG emissions (5% to 36% of total). The importance of consistency between water and energy demand management is highlighted, with a potential for perverse water use outcomes through solar hot water system installation observed. Finally, outcomes of this study show that effective demand management of combined water and energy use in households requires a focus on both human and physical characteristics.

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Contributions made to the authorship of the paper are as follows:

Contributor	**Statement of contribution**
Binks, A. N. (Candidate)	Designed analysis (90%) Wrote the paper (90%)
Kenway, S. J.	Designed analysis (5%) Edited paper (5%)
Lant, P. A.	Designed analysis (5%) Edited paper (5%)

5. <u>The effect of water demand management in showers on household energy use</u>

5.1. Introduction

There is a growing focus on integrated management of water and energy. Motivations include concerns about water and energy resource scarcity due to population growth (Kajenthira et al. 2012), and extend to food security issues (Hussey and Pittock 2012), economic efficiency (Kajenthira et al. 2012), climate change impacts (Pittock et al. 2013), and the implications of resource dependency on the adaptive capacity of cities (Newell et al. 2011). By taking advantage of synergies between water and energy efficiency, integrated water and energy management presents a significant opportunity to address urban resource challenges. In the water sector, the energy requirements of urban water resources have attracted particular attention as the sector seeks to address risks associated with energy-intensive supply options and expected growth in energy costs (Cook et al. 2012).

The combined energy use for urban water supply, water end use, and for provision of wastewater services represents 13-18% of state electricity use and 18-32% of natural gas consumption in Australia and the United States (Klein 2005, Kenway et al. 2011a). Of this, the energy used during water end use (in residential, commercial and industrial uses) comprises approximately 90% (Kenway et al. 2015). This indirect component of energy use for urban water is significant. In households in particular water use drives a significant proportion of energy use, with energy use for hot water heating in Australia estimated at 22% of total household energy use (Commonwealth of Australia 2008b). As improvements in building design continue to increase the efficiency of residential energy uses such as space heating, water-driven energy use will grow to be an increasingly significant fraction of overall household energy use (Tiefenbeck et al. 2014). Management of water-related energy use may therefore offer substantial opportunities for further efficiency gains as an 'indirect' lever for urban energy management.

The potential for water demand management programs to shift household water use has been well studied, however little is known about the impact of water demand management on household energy use. This information is important because utilities could use the information to simultaneously limit energy use for urban water service provision while supporting households to reduce household bills. If able to demonstrate that water demand management programs led to energy cost savings for consumers (in addition to water cost savings), it may support the development of a business case for investment in demand management initiatives (which are currently not viable due to consumption-dependent revenue). Consequently, this paper aims to use detailed modelling and household investigations to quantify the potential water and energy use impact of water demand management. This includes consideration of the influence of hot water system type on energy used for water heating, and quantification of the potential impact of demand management on water, electricity and natural gas bills.

5.1.1. Background

Of the literature quantifying the potential for of water-related energy management in households, the dominant focus of studies has been on the impact of fittings and technologies. Naspolini et al (2010) studied the energy saved in showering through a change in hot water system to solar electric boosted systems, in low-income communities in Brazil. Giglio et al (2014) also analysed the link between showers and hot water systems, studying the benefits of low-cost solar hot water systems for different socio-economic groups. Beal et al (2012) investigated the impact of efficient technologies on water and energy end use in households. They noted that a major driver of water-related energy use is the type of hot water system installed and the percentage of hot water demanded from the hot water system, and highlighted that showers and hot water tap usage consumed most energy and generated most annual carbon emissions per capita (Beal et al. 2012).

While a focus on efficient fittings and technologies is critical, several authors point out that as the increasing efficiency of appliances approaches maximum limits, hardware-focused demand management will have limited further potential. For example, this is noted in studies assessing the impact of informational feedback on energy consumption (Faruqui et al. 2010) and the determinants of replacement of home appliances (Fernandez 2001), and in exploring potential models for service-oriented infrastructure (Roelich et al. 2015). A focus on behaviour is therefore likely to yield greater efficiencies than a focus only on hardware. Gill et al (2011) note in a study of 25 dwellings of homogenous, low-carbon design, water consumption was found to vary between dwellings by a factor of greater than 7 and energy consumption by a factor of greater than 3, concluding that occupant behaviour must be targeted in addition to efficient design to ensure resource efficiency. This is supported by the analysis of Kenway et al (2016), who note that behavioural aspects had a greater influence on household water-related energy use than technical aspects.

Despite recognition of the importance of behaviour, few studies quantify the potential impacts of behaviour-focused demand management on water-related energy use, and those which do quantify this potential are based on basic theoretical modelling of an ‘average case’. For example, Maas (2009) calculates the potential environmental benefits of shower duration management for an average Canadian household, using estimated water use and energy intensity characteristics. Zhou et al. (2013) use a water balance model of Changzhou (China) to estimate supply-side energy use for urban water services, using sector-specific water and energy data collected through on-site visits, literature review and estimations. The energy impact of a 10% reduction in domestic water consumption (compared to the national average) is estimated, under the assumption that half of the water reduction occurs through showers.

While these studies provide valuable context on the potential for end-use focused water-related energy management in households, the authors argue that there is a gap in the current literature, in that quantification of the potential for water-related energy demand management has not considered the complexity of differences in both behaviour and technology between households. Analysis based on the ‘average case’ fails to capture the complexity of household conditions which will underpin the success or failure of the interventions required to achieve demand management goals. Kenway et al. (2016) draw attention to the wide range of assumptions for the average case that are evident in literature (e.g. cold water temperatures vary from 4.4°C (Arpke and Hutzler 2006) to 20°C (Cheng 2002)), emphasizing that variation in individual conditions between households will have a significant influence on water-related energy use and management potential. Binks et al. (2016) further highlight the significance of varying conditions between households, demonstrating that differences in individual water and energy use characteristics between seven households led to a range in water-related energy use of between 2 and 7 kWh p^{-1} d^{-1}.

The current study aims to capture the impact of such variation in these individual household characteristics, and their subsequent impact on the potential for energy management through water demand management, through the use of detailed and validated models for five highly characterised individual households in Melbourne, Australia. The individual household characteristics which modify this potential are identified, providing valuable information for resource managers and policy makers to more effectively tailor interventions towards the conditions which are likely to yield greatest impact while avoiding adverse outcomes.

5.1.2. Objectives of study

This paper will quantify the impacts of a water demand management scenario for five Australian households, and identify the influential factors leading to differences in these impacts between households. The analysis will address the following research questions: (a) what is the potential water and energy saving associated with a 4-minute shower water demand management program? (b) what impact does the type of hot water system installed have on energy use for hot water heating? and (c) what is the combined water and energy cost saving to the household as a result of the demand management scenario?

5.1.3. Article structure

The methodology applied to this study is outlined in Section 2, including a description of the existing household models used in analysis and the design and application of scenarios for analysis through these models. Scenario analysis results are presented in Section 3 in three stages: the impact of a 4-minute shower scenario on the water use, energy use and related costs for the existing households in comparison to the baseline study (Section 3.1); the influence that different hot water system types would have on the water-related energy use impacts of a 4-minute shower scenario in the existing households, in comparison to their baseline shower durations (Section 3.2); and the fixed and variable water and energy cost impacts of the above scenario (Section 3.3). This is followed by discussion of the analysis outcomes, and a summary of the key conclusions of the study.

5.2. Methodology

This study was conducted using existing mathematical material flow analysis (MMFA) models of five Melbourne households, which have been previously described in detail by Binks et al. (2016). The current study simulates responses to hypothetical management scenarios in these households.

The methodology for this study focuses on analysis of two sets of demand management scenarios, conducted by modifying key parameters within the existing ResWE household models developed by Binks et al. (2016). A schematic diagram of this study approach is provided in Figure 9. The analyses performed were as follows:

(a) 4-minute shower scenario: what impact would shifting the behaviours of these households to a four minute shower duration have on their water use, hot water system energy use, and combined water and related energy costs?

(b) Hot water system (HWS) type + 4-minute shower scenario: what impact would the installation of different types of hot water systems in these households have on their energy use and combined water and related energy costs, at baseline shower duration and in response to the 4-minute shower scenario?

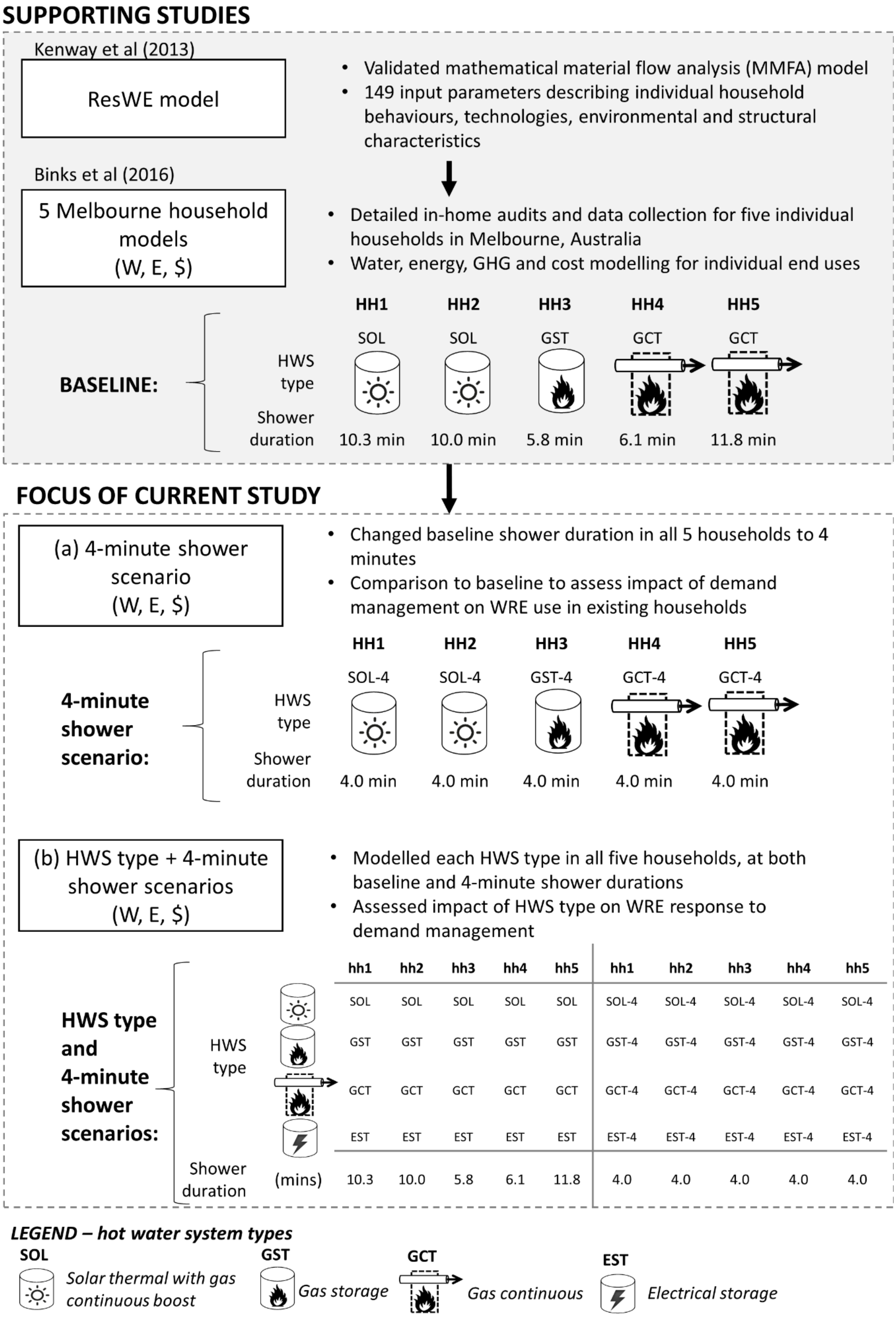

Figure 9: Schematic diagram of study approach; W= water, E= energy, $= costs

5.2.1. ResWE mathematical material flow analysis model (Kenway et al 2013)

The ResWE model was developed and validated by Kenway et al. (2013b) to understand energy use influenced by water use in households. ResWE is a mathematical material flow analysis (MMFA) model based on 149 input parameters describing technical, behavioural, structural, environmental and occupancy characteristics of a household. These parameters define ten ‘service’ subsystems, which provide the household with services such as drinking water, water for showering, dishwashing and laundry, flushing toilets and evaporative cooling. These service subsystems are supplied with water and energy from ‘supply’ subsystems (including electricity supplies, natural gas supplies and/or solar thermal sources). Major flows of cold water, hot water, energy and wastewater are identified. The other remaining household services which involve energy use (but not water use) are described in the ‘other energy use’ subsystem, to allow complete accounting of total water and energy use in the household. Additional model inputs include water, electricity and natural gas supply tariff information, and greenhouse gas (GHG) emissions factors associated with electricity and natural gas supplies. Outputs of the ResWE model comprise quantitative data on water use, energy use (electricity, natural gas and/or solar thermal), utility costs, and greenhouse gas emissions (GHGs) associated with each individual end use within the households.

A conceptual diagram of the model is provided in Figure 10.

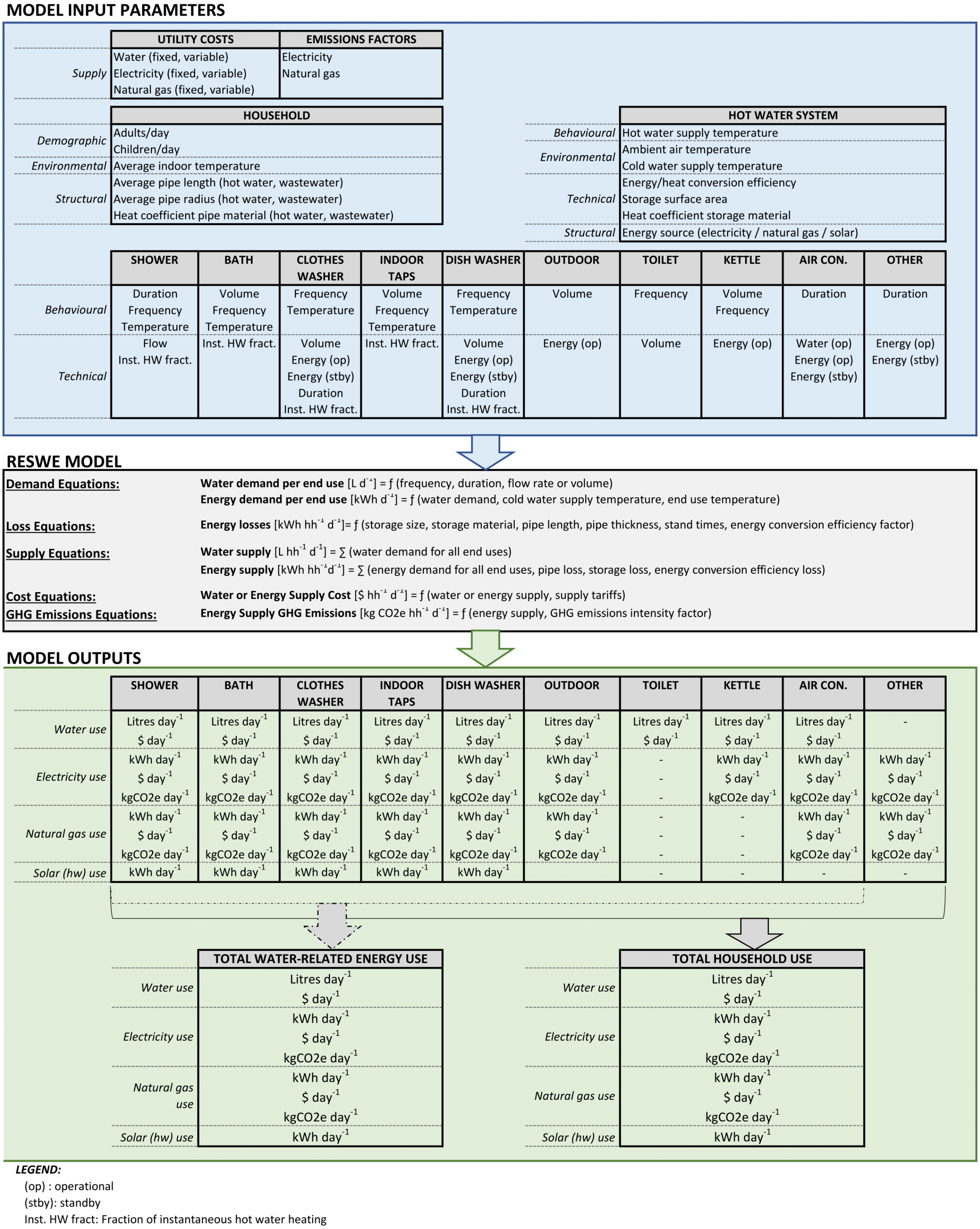

Figure 10: Conceptual diagram of ResWE model (source: Binks et al. (2016))

5.2.2. Melbourne household models (Binks et al. 2016)

Binks et al (2016) characterised the water and related energy use of the five Melbourne households under analysis using the ResWE model described in section 5.2.1. These five household models have been adopted as the baseline for this study, as their detailed characterisation of individual household characteristics allows for analysis of the influence of both behavioural and technological influences in shower water-related energy demand management.

The 149 input parameters for the ResWE models in the Binks et al. (2016) study were based on empirical data describing behavioural, technological, structural, environmental and occupancy characteristics of each household. This empirical data was collected from each household through physical audits, interviews and analysis of water meter data, focused on a single year (April 2012-March 2013). Data collected was used to define a mean and standard deviation value (over one year) for each model input parameter.

The significant detail of the empirical data required resulted in an audit and interview process which could be considered intrusive and time-intensive for the household participants. Selection of households for the study therefore prioritised access to data, an understanding and willingness to participate in the intrusive data collection procedures, and long-term availability of participants for repeat visits to confirm parameters. Selection of households drew from a pool of Yarra Valley Water employees engaged in a concurrent water use study, in order to satisfy accessibility requirements and to take advantage of the detailed water use dataset available. The focus of the study was on detailed description of water and energy use conditions within individual households, and was not intended to provide a representative sample of household types within the broader population.

Key characteristics of the five Melbourne households described by Binks et al. (2016) are summarised in Table 16 (average values over one year). The households vary according to occupancy, hot water system type and size, and behavioural (e.g. shower duration), structural (e.g. length of hot water pipes) and environmental (e.g. cold water supply temperature) characteristics. All five households are detached dwellings.

Table 16: Key household characteristics - mean values over one year (Source: Adapted from Binks et al. (2016))

End Use	Parameter	HH1	HH2	HH3	HH4	HH5
Year of analysis		Apr 2012 – Mar 2013				
Occupancy	Adult residents (p hh^{-1} d^{-1})	4	4	2	2	2
	Child residents (p hh^{-1} d^{-1})	-	-	2	2	-
	Average occupancy[a] (p hh^{-1} d^{-1})	3.65	3.04	3.42	3.95	1.73
Hot water system	Type[b]	SOL+GCT[c]	SOL+GCT[c]	GST	GCT	GCT
	Cold water supply temperature (°C)	16.7	16.3	16.3	15.6	16.9
	Hot water temperature (°C)	60	60	60	60	60
	Storage surface area (m^2)	2.8[d]	1.8[d]	1.8	-	-
	Average length hot water pipe (m)	8	12	5	15	7
	Energy conversion efficiency factor (-)[e]	1.54[f]	1.54[f]	1.31	1.54	1.54
Shower	Frequency (showers p^{-1} d^{-1})	1.6	1.8	0.9	0.9	1.4
	Duration per shower (min)	10.3	10.0	5.8	6.1	11.8
	Flow rate (L min^{-1})	6.0	9.0	4.4	10.5	7.4
	Temperature (°C)	40	41	32	38	43

[a] Based on annual calendar of occupancy for 2012-13, including guests and absences

[b] **SOL**: Solar thermal; **GCT**: Gas continuous; **GST**: Gas storage

[c] Solar thermal hot water system with gas continuous booster unit. Gas continuous booster load assumed at flat rate of 20% of total hot water energy demand

[d] Solar thermal hot water storage

[e] Energy conversion efficiency factor = η^{-1}, where η is the efficiency of the hot water system.

This factor is used to convert the net thermal energy required to heat water to gross thermal energy consumed by the hot water system during the energy-to-heat conversion process.

This factor applies to energy conversion processes within the household only (i.e. does not account for the loss of thermal energy in the generation of electricity and/or other life-cycle energy impacts).

[f] Applied to gas continuous component of hot water supply only

Water, electricity and natural gas supply tariffs adopted for the study are outlined in Table 17. Water supply tariffs for the study period (April 2012 to March 2013) were provided by Yarra Valley Water. Electricity and natural gas tariffs were adopted from standing offer arrangements reported by St Vincent de Paul (SVP) for the study period, based on detailed tariff tracking conducted by SVP spanning all domestic retailers and supply zones in Victoria (Mauseth Johnston 2015a, Mauseth Johnston 2015b). For electricity and natural gas tariffs, an average of standing offer tariffs for all available retailers within the study area was adopted. Data on actual electricity and natural gas market tariffs for each household were collected during surveys, however a standardised tariff was adopted for analysis to allow consistent cross-comparison of modelled water, electricity and gas costs between the households.

Table 17: Supply tariffs adopted - water, electricity and natural gas (Source: Binks et al. (2016))

	Water		**Electricity**		**Natural Gas**	
Tariff	*Fixed*	*Variable*	*Fixed*	*Variable*	*Fixed*	*Variable*
	\$AU y^{-1}	*\$AU L^{-1}*	*\$AU y^{-1}*	*\$AU kWh^{-1}*	*\$AU y^{-1}*	*\$AU kWh^{-1}*
	441.76	0.0037	341.28	0.2678	215.68	0.0625

Results of the ResWE models for each of the studied households are summarised in Table 18 (adapted from Binks et al. (2016)).

Table 18 Overview of average daily household water and related energy use (Source: Adapted from Binks et al. (2016))

		HH1	HH2	HH3	HH4	HH5
Water use	L hh^{-1} d^{-1}	733	737	305	545	333
Water-related energy (WRE) use	kWh hh^{-1} d^{-1}	16	21	7	15	12
Total energy use[1]	kWh hh^{-1} d^{-1}	70	164	52	100	49
Modelled WRE % Total Energy		**23%**	**13%**	**13%**	**15%**	**24%**
Water and WRE costs	\$ hh^{-1} d^{-1}	\$5.78	\$5.15	\$3.52	\$5.02	\$3.86
Total water and energy costs[2,3]	\$ hh^{-1} d^{-1}	\$12.24	\$19.13	\$9.53	\$14.05	\$8.47
Modelled W&RE % Total Costs		**47%**	**27%**	**37%**	**36%**	**46%**

[1]Based on empirical energy billing data

[2]Costs for total household water and energy use, including the non water-related components of energy use (e.g. lighting, heating).

[3]Calculated based on empirical utility data for electricity and natural gas use, using supply tariffs in Table 17.

5.2.3. Scenario analysis design

5.2.3.1. End use demand management through shower duration

A demand management scenario consisting of a shift to a four minute shower duration in each of the households studied has been adopted for scenario analysis.

Shower duration was adopted as the focus of demand management in this study for several reasons: (i) showers were identified as a significant WRE end use by Binks et al. (2016) (14% to 67% of household water use, and 11% to 67% of household WRE use, in both cases increasing with shower duration and total volume of water use); (ii) four-minute showers are a well-recognised residential water demand management strategy in Australia; and (iii) shower duration is a behavioural factor which may be more readily controlled by households, compared to shower temperature (difficult to shift without changing comfort level), shower flow rate (low-flow shower heads already at high market penetration, cost of fittings) and shower frequency (lifestyle factors). This approach is supported by findings in literature, in which focussing scenarios on individual end use has been identified as an effective approach for water-related energy demand management (Fidar et al. 2010, Strengers 2011a, Kenway et al. 2016, Escriva-Bou et al. 2015), and the potential of behaviour change initiatives has been noted (Gill et al. 2011, Kenway et al. 2013b, Maas 2009, Escriva-Bou et al. 2015).

5.2.3.2. Hot water energy use and loss in households

Hot water system types vary according to energy source, and method of hot water heating and/or storage. The energy used by a hot water system to supply hot water to an end use can be described as three main components: (i) energy for hot water; (ii) losses from the hot water system (including storage heat losses, and energy conversion efficiency losses); and (iii) pipe heat losses during hot water transport. The magnitude of each of these energy use components will be affected by the characteristics of the end use, the hot water system, and of the household.

Storage losses and conversion efficiency losses for hot water systems were shown by Binks et al. (2016) to be significant components of water-related energy use in the five Melbourne households studied. According to the type of hot water system installed, these components of hot water system energy use will respond differently to changes in end use. To account for these differences, any demand management scenario analysis should consider water-related energy use responses not only at the point of use but also at the hot water system.

Four types of hot water system common in Australia have been considered in this study – gas continuous, gas storage, electric storage, and solar thermal hot water systems with continuous gas boost. The key characteristics of these types of system are summarised in Table 19.

Energy losses from hot water storages have been estimated for each household based on a heat transfer relationship between: the surface area of the household hot water storage; the thermal properties of the storage material; and temperatures of ambient air, cold water, and hot water for that household.

Energy losses due to the energy conversion efficiency of the hot water system have been estimated by applying an energy conversion efficiency factor to the total energy for hot water heating (i.e. hot water energy, and storage energy losses). The energy conversion efficiency factor for each hot water system type studied is listed in Table 19.

Table 19: Hot water system types and characteristics

Hot water system type	**Description**	**Energy Conversion Efficiency Factor[a]**
Gas continuous (GCT)	Hot water is heated on demand by a natural gas fired unit, and distributed throughout the household to hot water end uses. Hot water temperature can be changed (using an electronic monitor) to suit individual end uses.	1.54
Gas storage (GST)	A volume of water in a hot water storage is maintained at a set temperature, by a gas fired unit, and hot water for end use is drawn from this storage as needed.	1.31
Electric storage (EST)	A volume of water in a hot water storage is maintained at a set temperature, by an electric element, and hot water for end use is drawn from this storage as needed.	1.02
Solar thermal with continuous gas boost (SOL)	A volume of water in a hot water storage is heated by solar energy, and is drawn from the storage as needed. As the hot water feeds into the household on demand, this hot water is boosted (if required) by a gas continuous hot water system to meet a set hot water temperature prior to delivery to the end use.	NA

[a] Energy conversion efficiency factor = η^{-1}, where η is the efficiency of the hot water system. Data from Flower (2009).

5.2.4. Scenario analysis methodology

Scenario analysis was undertaken by applying demand management scenarios to the ResWE models created by Binks et al. (2016) (described in section 5.2.2). This was achieved by varying the ResWE model parameters as outlined in Table 20.

Table 20: Demand management scenarios - parameters for shower duration and hot water systems

Scenario	Shower duration (minutes) HH 1	HH 2	HH 3	HH 4	HH 5	HWS energy source	HWS type	Energy conversion efficiency factor (-)	Hot water storage surface area (m^2) HH 1	HH 2	HH 3	HH 4	HH 5
SOL	10.3	10.0	5.8	6.1	11.8	SOL + GAS	SOL + GCT	1.54[a]	2.8	1.8	1.8	1.75[b]	1.75[b]
SOL-4	4.0	4.0	4.0	4.0	4.0								
GCT	10.3	10.0	5.8	6.1	11.8	GAS	GCT	1.54	-	-	-	-	-
GCT-4	4.0	4.0	4.0	4.0	4.0								
GST	10.3	10.0	5.8	6.1	11.8	GAS	GST	1.31	2.8	1.8	1.8	1.8[b]	1.8[b]
GST-4	4.0	4.0	4.0	4.0	4.0								
EST	10.3	10.0	5.8	6.1	11.8	ELEC	EST	1.02	2.8	1.8	1.8	1.8[b]	1.8[b]
EST-4	4.0	4.0	4.0	4.0	4.0								

[a] applied to energy demand for gas continuous boost system only

[b] assumed based on 150 L storage tank size

5.2.5. Scope of analysis

For the purposes of this study, water-related energy use is the direct energy use associated with water end uses within the household. The energy use associated with water supply or wastewater collection and treatment are not included.

5.3. Results

5.3.1. Household water use, energy use and cost responses to demand management scenario

Impacts of the demand management scenario on total household water use are summarised in Figure 11 (a and d). In response to the four minute shower scenario, total daily water use for each of the five households dropped from between 88 and 242 L p^{-1} d^{-1} to between 83 and 145 L p^{-1} d^{-1} (Figure 11a). This represents a reduction in total household water use of between 6% (HH3) and 42% (HH5) (5 to 97 L p^{-1} d^{-1}, Figure 11d). The shower demand management scenario has most impact in households with higher baseline water use (HH1, HH2 and HH5), in which shower water use represents a higher fraction of total household water use (see Binks et al. (2016)).

A comparison of hot and cold water use for the households (Figure 11a and d) shows that hot water use is most impacted by the four-minute shower scenario, reducing by between 11% and 65% of total baseline hot water use for the household. This is due to the fact that showers are responsible for the largest fraction of hot water use compared to other end uses in these households (Binks et al. 2016).

Average daily energy use for hot water systems in the five households ranges from 1.5 to 6.2 kWh p^{-1} d^{-1} (including solar thermal energy for hot water heating) (Figure 11b). Shifting these households to four minute showers would reduce hot water system energy use to between 1.3 and 3.2 kWh p^{-1} d^{-1} . This represents a reduction in energy use of between 0.1 and 3.8 kWh p^{-1} d^{-1} across the households (Figure 11e), or a reduction of 9% (HH3) to 63% (HH5) from baseline hot water system energy use. Greatest reductions would be achieved in households with higher baseline shower durations and frequencies (HH1, HH2 and HH5: 10 - 12 min $shower^{-1}$, 1.4 - 1.8 showers p^{-1} d^{-1}).

Combined baseline costs for water and hot water system energy for the households studied range from \$993 to \$1559 hh^{-1} y^{-1}. Shifting to four-minute showers would reduce combined water and hot water system energy costs to between \$812 and \$1459 hh^{-1} y^{-1}, a reduction of between \$37 (HH3) and \$500 (HH2) hh^{-1} y^{-1} (or between 4% to 31% of baseline water and hot water system energy bills). Greatest reductions would be achieved in households with higher baseline shower durations and frequencies (HH1, HH2 and HH5: 10 – 12 min $shower^{-1}$, 1.4 - 1.8 showers p^{-1} d^{-1}). This reflects similar observations for energy reductions (see section 5.3.2).

Bills are dominated by water costs, which comprise 76% to 95% of combined baseline water and hot water system energy costs, rising to 78% to 97% under a four-minute shower scenario. Under a four-minute shower scenario, water costs reduce by \$25 to \$436 hh-^{1} y^{-1} (3% to 29% of baseline water bills), while energy costs reduce by \$12 to \$179 (9% to 63% of baseline hot water system energy bills).

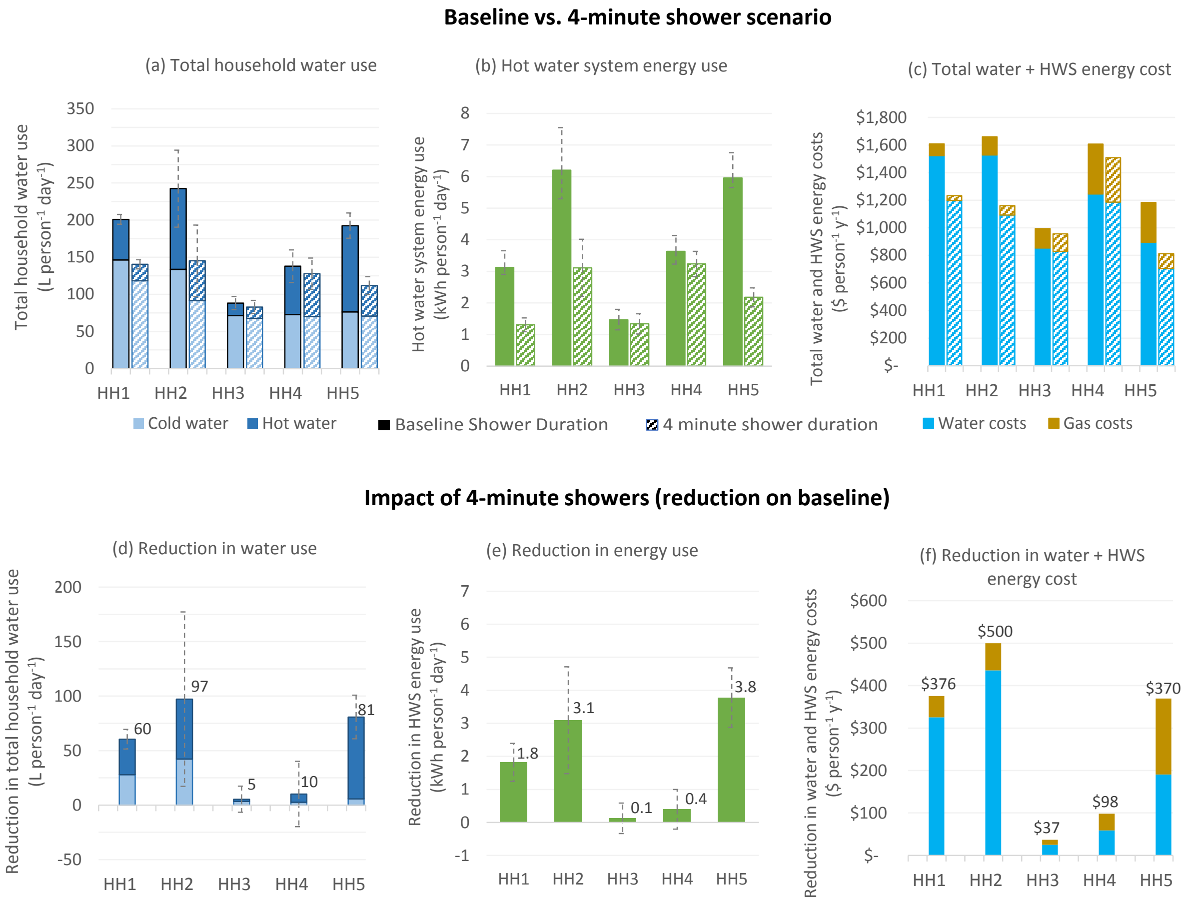

Figure 11: Total daily water use, hot water system energy use and combined water and energy costs, per person, for baseline and 4-minute shower scenarios. (Error bars show one standard deviation around the average.)

5.3.2. Hot water system type and impact upon energy use in response to demand management

The impact of hot water system type on daily hot water system energy use for each household studied is summarised in Figure 12. The hot water system energy use is shown in terms of energy use components (energy losses, hot water energy, and solar thermal energy), for both the baseline and four-minute shower scenarios.

At their baseline shower durations, in four of the five households studied a gas continuous hot water system (GCT) would consume the greatest energy for hot water heating (Figure 12; HH1, HH2, HH4 and HH5). This is due to the fact that energy losses would be greatest for gas continuous type systems in these households. For HH3, which has the most conservative volume and temperature for shower water use (23 L p^{-1} d^{-1} at 32°C, see Table 16), a gas storage system (GST) would consume most energy for hot water heating. Combined energy conversion efficiency losses and storage losses for a gas storage system (GST) would outweigh energy conversion efficiency losses in a gas continuous system (GCT) in this household.

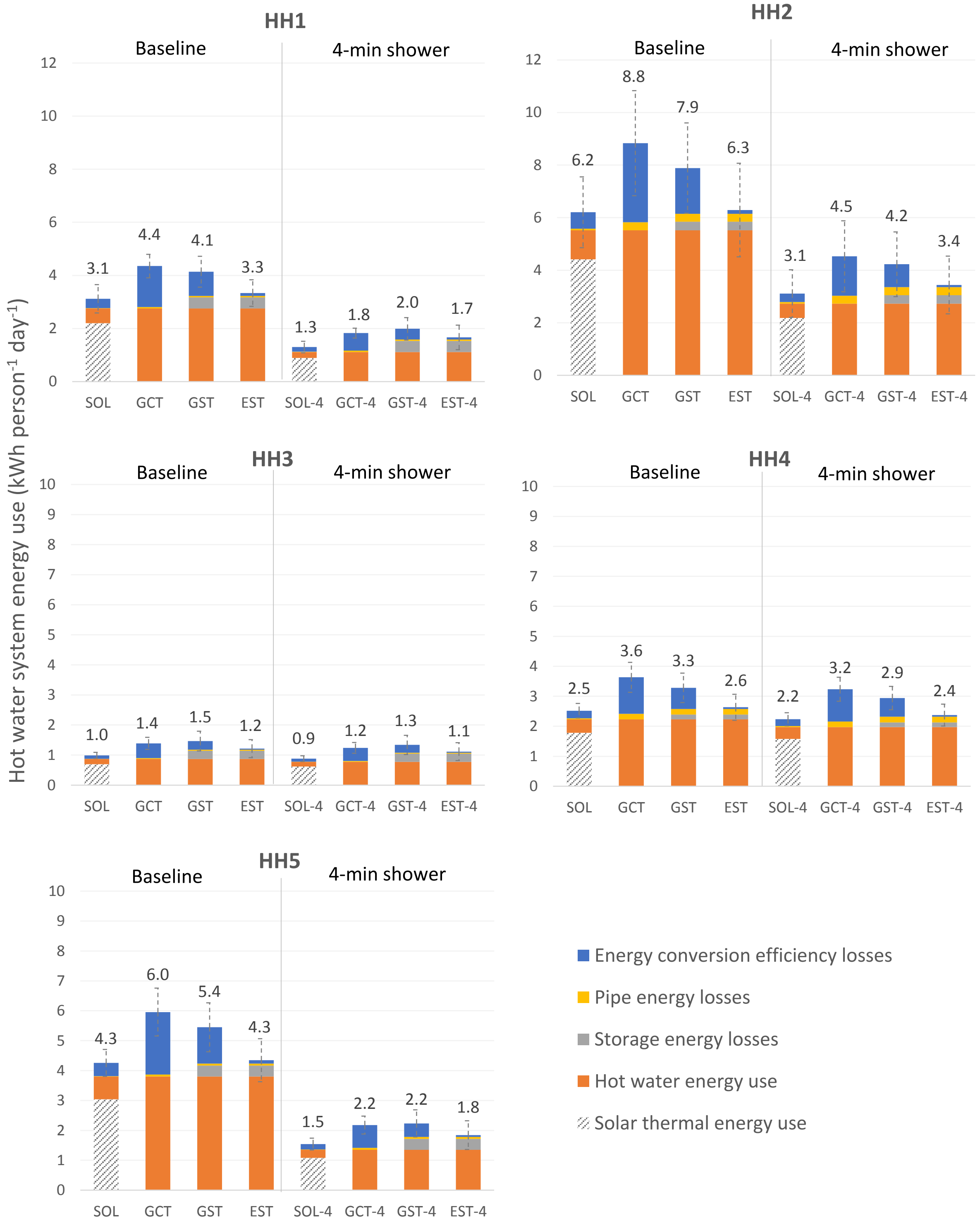

Figure 12: Average daily hot water system energy use, per person, by hot water system type and shower scenario (kWh p^{-1} d^{-1}). (Error bars show one standard deviation around the average.)

Across all five households at their baseline shower durations, solar hot water systems with gas continuous boost (SOL) would use least energy for hot water heating (1.0 to 6.2 kWh p^{-1} d^{-1}). Electric storage hot water systems would consume less energy than gas storage or continuous hot water systems within all households studied under both current (EST) and four-minute (EST-4) shower durations.

Under the 4-minute shower demand management scenario, in households with higher shower flow-rates (HH2, HH4 and HH5, 9 – 10 L min^{-1}, see Table 16) a gas continuous hot water system (GCT-4) would consume most energy for hot water. In the households with lower flow showers however (HH1 and HH3, 4.4 – 6 L min^{-1}), a gas storage system (GST-4) would consume most energy under the demand management scenario. This is due to the fact that energy conversion efficiency losses scale directly with reduced hot water demand, whereas storage losses are relatively fixed (as a function of the surface area of the hot water system, and the temperature difference between hot water stored and the ambient air outside the storage tank).

Energy conversion efficiency losses would comprise 33% - 36% of total hot water system energy use for a gas continuous hot water system in all households, under both current (GCT) and four-minute (GCT-4) shower durations. Storage losses, which do not scale directly with use, would comprise 4% - 19% of hot water system energy use for a gas storage system at baseline shower duration (GST), increasing in significance to 5% - 21% under four-minute showers (GST-4). In particular, in the households with higher baseline shower durations and frequencies (HH1, HH2 and HH5), storage losses in gas storage systems approximately double their proportion of total hot water system energy use under four-minute showers. This is due to the fact that these households see a greater reduction in energy use for water heating under the demand management scenario, and the relatively fixed volumes of storage loss therefore comprise a greater proportion of the reduced total hot water system energy use.

An electric storage system would have lower combined household energy losses (pipe, storage and energy conversion efficiency losses) than either a gas storage or continuous system in all households studied, under both current (EST) and four-minute (EST-4) shower durations. This is due to lower energy conversion efficiency losses for electric storage hot water systems (energy conversion efficiency factor 1.02, see Table 19). For a solar thermal hot water system with gas continuous boost, energy losses (through gas continuous system energy conversion efficiency) would comprise 10% to 11% of total hot water heating energy at baseline shower durations across the five households, increasing to slightly 10% to 12% under four-minute showers. (Energy losses from solar hot water storage are not considered).

5.3.3. Water and energy fixed and variable costs and response to shower demand management

Water and energy costs for hot water system operation for the households studied under each scenario are summarised in Table 21. These costs are broken down into the fixed and variable cost components of utility bills in Figure 13.

Table 21: Annual water and related energy costs, per household per year, by household and utility type

	Baseline shower duration ($ hh^{-1} y^{-1})					4-minute shower duration ($ hh^{-1} y^{-1})				
	Hot water system energy costs				Water costs	Hot water system energy costs				Water costs
Scenario	**SOL**	**GCT**	**GST**	**EST**	**All**	**SOL-4**	**GCT-4**	**GST-4**	**EST-4**	**All**
Energy source[a]	NG	NG	NG	EL		NG	NG	NG	EL	
HH1	$85	$413	$393	$1,362	$1,474	$35	$174	$190	$706	$1,148
HH2	$131	$649	$580	$2,029	$1,479	$67	$334	$312	$1,129	$1,043
HH3	$27	$133	$140	$492	$853	$24	$119	$128	$453	$828
HH4	$74	$362	$327	$1,153	$1,196	$65	$323	$294	$1,042	$1,137
HH5	$60	$286	$263	$910	$896	$22	$107	$110	$415	$705

[a] NG = natural gas, EL = electricity

Under all scenarios except for those with electric storage hot water systems, water bills are the dominant component of total water and related energy costs for all households (Figure 13). These represent between 69% - 86% (GCT) and 92% - 97% (SOL) of baseline costs, rising to between 76% - 87% (GCT-4) and 94% - 97% (SOL-4) of costs under the four minute shower scenario. The fixed component of water costs is the greater component of these, comprising 21% - 45% (GST) to 27% - 50% (SOL) of baseline combined water and related energy costs, and 31%-54% (GST-4) to 37% - 61% (SOL-4) under the four-minute shower scenario. This is a result of higher proportional fixed costs for water than for the water-related energy component of natural gas bills ($442 h^{-1} y^{-1} for water vs. $71 to $326 hh^{-1} y^{-1}).

Hot water system energy costs for electric storage systems (EST, Figure 13) would be significantly higher than other system types for all five households studied, due to comparatively higher cost per kilowatt-hour for electricity than for natural gas supply ($\$0.2678$ kWh^{-1} vs $\$0.0625$ kWh^{-1}, see Table 17). These systems would therefore see significant water and related energy cost savings under a four minute shower scenario (scenario EST-4). At baseline shower durations, with electric storage hot water systems installed (scenario EST) the households studied would pay between $492 and $2,029 hh^{-1} y^{-1} for electricity for hot water system operation. Under a four-minute shower scenario (EST-4) this electricity cost would decrease to $453 to $1,129 hh^{-1} y^{-1}, a reduction of between $39 hh^{-1} y^{-1} (HH3) to $900 hh^{-1} y^{-1} (HH5) or 8% to 54% of hot water system electricity use.

Energy costs for gas powered hot water systems under baseline shower durations would range from $133 to $649 hh^{-1} y^{-1} for gas continuous systems (GCT), and from $140 to $580 hh^{-1} y^{-1} for gas storage systems (GST). Shifting to four-minute showers would reduce these annual costs to $107 to $334 (GCT-4) and $110 to $312 (GST-4), comprising annual reductions of $14 to $315 (11% - 63%) and $5 to $269 respectively (4% - 58%). Greatest energy cost reductions (46% - 58% and 44% - 54%) are evident in households with higher baseline shower durations and frequencies (HH1, HH2 and HH5: 10 - 12 min $shower^{-1}$, 1.4 – 1.8 showers p^{-1} d^{-1}).

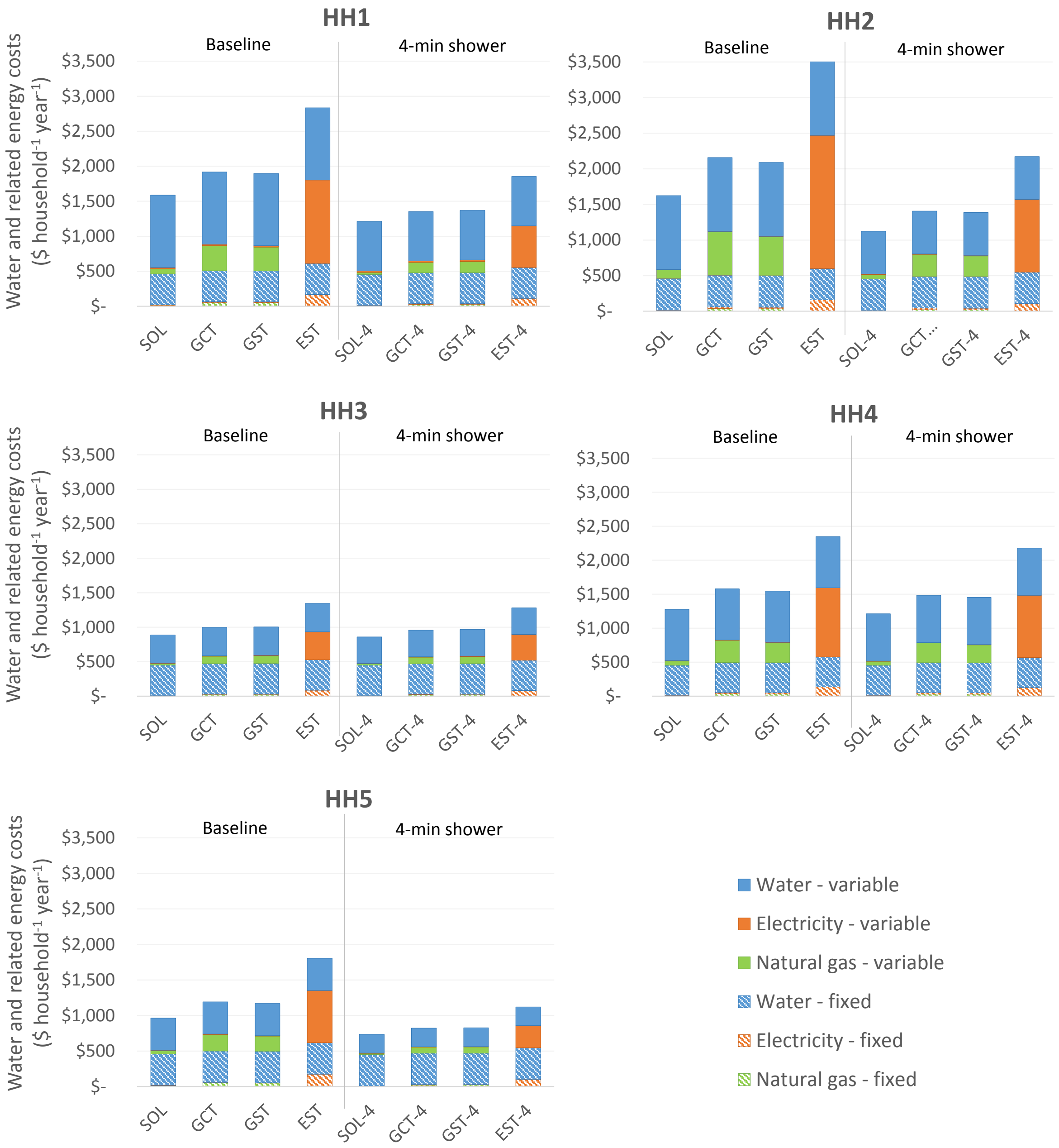

Figure 13: Annual household water and -related energy costs, per household per year, by cost component

5.4. **Discussion**

Demand management through a four-minute shower scenario would reduce hot water heating energy use by 0.1 to 3.8 kWh p^{-1} d^{-1} (or 9% to 64%) for the households studied. When compared with the total energy use by Melbourne water utilities in 2009/10 of approximately 0.3 kWh p^{-1} d^{-1} (1,505,107 GJ y^{-1} for 3,977,783 people serviced, from Cook et al. (2012)), shower demand management in four of the five households studied has the potential to more than offset all of the energy required for the provision of their water services, in some cases by a factor of more than ten (HH2 and HH5), as illustrated in

Figure 14. The most conservative household studied (HH3) is still estimated to achieve a saving of approximately 30% of the energy required for service provision (*Figure 14*). This validates well with existing literature for Australia, the UK and the US. For example, Kenway et al. (2008) estimate residential water heating to be 1.3% of total energy used in Australian cities in comparison to 0.2% used by water utilities; DEFRA (2008) estimate residential water heating to be 5.5% of total GHG emissions in the UK in comparison to 0.8% for the potable water sector. Similarly, life cycle analysis performed by Arpke and Hutzler (2006) in the US showed that 93% to 97% of energy consumed during the operational life cycle of domestic water use was within buildings for water heating. Results of this study suggest that the energy savings potential through residential shower demand management is significant. Such a saving would benefit a water sector under pressure to increase energy productivity, if the consequent energy savings to households could be quantified and demonstrated.

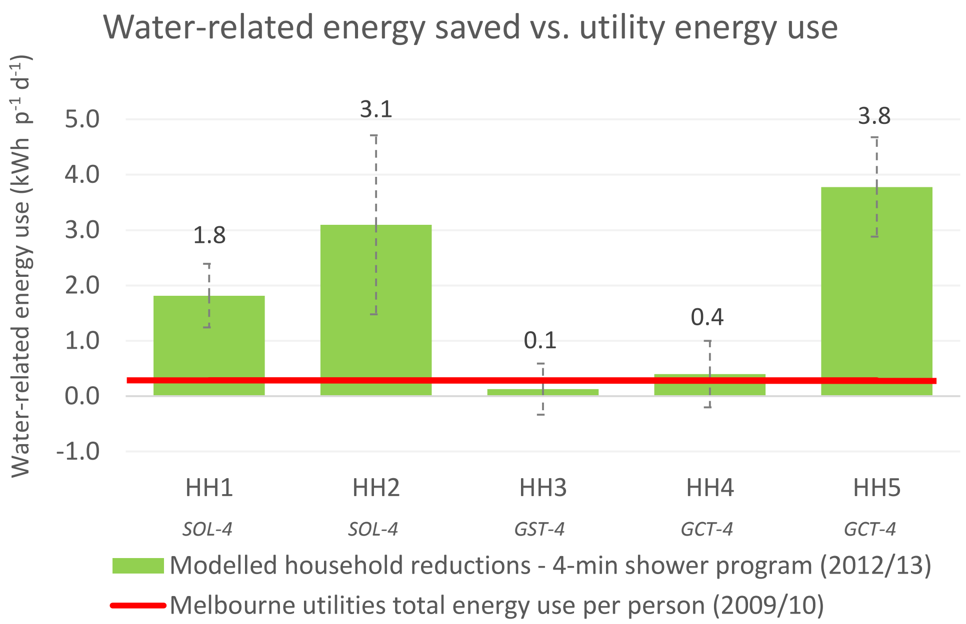

Figure 14: Average water-related energy saved through 4-minute shower scenario, per person per day, compared to utility energy use for service provision. (Error bars show one standard deviation around the average).

Demand management programs may also offer water utilities the potential to offset rising costs of essential services and thereby meet their obligations to consumers. For the households studied, a shower-focused demand management program could reduce household costs for combined water and energy use by \$37 to \$500 y^{-1}, approximately \$12 - \$179 of which is energy cost savings for natural gas. This represents a 9% to 63% saving on baseline natural gas costs for hot water system use in these households. Such savings could be particularly significant for the lowest earning 20% of households in Victoria, who spend almost three times as much of their disposable income on domestic fuel and power compared to the average household in Victoria (6.3% vs. 2.2%, CUAC (2014)). Low income households in Victoria receive support from the state Government to meet household water and energy costs in the form concessions on their water and energy bills. If utilities are able to quantitatively demonstrate reductions in water and related energy costs achieved in low income households through targeted water demand management programs, and subsequently demonstrate a reduction in government subsidy payments for concessions, utilities may have an opportunity to build a strong business case for efficiency initiatives (which currently are not economically rational due to negative revenue impacts).

Demand management impacts vary depending on the drivers for efficiency. For example, simulating different hot water system types in each of the households studied found that an electric storage hot water system would consume less energy for water heating than either a gas continuous or a gas storage type system (due to significantly lower point of use energy conversion efficiency losses), but would cost substantially more to run (due to higher cost per kilowatt-hour under electricity tariffs). Furthermore, electric storage systems require significantly more primary energy than gas systems (approximately 3 kWh of thermal energy required to generate 1 kWh of electric energy (Kenway et al. 2011a)), and will have higher greenhouse gas emissions associated with electricity consumption (emissions intensity 1.17 kg CO2-e kWh^{-1} for electricity vs. 0.18432 kg CO2-e kWh^{-1} for natural gas in Victoria, (Commonwealth of Australia 2013)). This means that for the households studied, if aiming for lowest household energy consumption an electric storage hot water system would be a better choice than a gas storage or continuous system, however if the aim was lowest cost, primary energy use or emissions, a gas storage or continuous system would be the preferred option. This reinforces the need for a focus on suitable indicators for communication and management of household consumption.

Water bills are currently the dominant cost driver for shower demand management in the households studied, at 76% - 95% of combined baseline costs for water and energy (gas) for water heating (Figure 11). Energy costs would become a more compelling driver for demand management if electric storage hot water systems were installed, in which case electricity costs comprise 37% to 58% of baseline bills for water and energy for hot water heating (scenario EST, Table 21). This reflects the fact that electricity tariffs currently comprise a much higher cost per kilowatt-hour than gas tariffs in Victoria (Table 17).

However, gas prices are forecasted to rise substantially (CUAC 2014), so the financial case for saving gas used for household water heating may become increasingly compelling.

Selection of efficient hot water systems for households should consider characteristics of the household and anticipated water use patterns. Under the demand management scenario, gas continuous systems were found to be more efficient for lower flow households (HH1 and HH3, 4.4 – 6 L min^{-1}), whereas for higher flow households (HH2 and HH4, 9 – 10.5 L min^{-1}) gas storage systems were found to be more efficient. Gas continuous hot water systems were most responsive to changes in demand, as conversion efficiency losses scaled directly with use. These systems are therefore likely to be the most beneficial in small households, or households with significant fluctuations in occupancy, as energy use for hot water heating will scale more directly with changes in usage and will therefore be minimised during low use periods. Storage systems would be better suited to large households with stable occupancy, as greater volumes of hot water usage will reduce the proportional storage losses. However, it is important to note that as hot water use decreases, the fixed volume of storage losses increase in importance (comprising a higher fraction of total energy for hot water heating). Selection of appropriate storage size will therefore become increasingly important as the efficiency of fittings and fixtures in households improves and reduces hot water demand. (See Vieira et al. (2014) for valuable work in this area).

5.4.1. Limitations

This study provides a scenario analysis for water-related energy demand management in five highly characterised individual households, with a focus on the impacts of shower duration and hot water system type on water and energy use and costs. Outcomes for these five households are not intended as a representative sample of the broader population. The objective of the study is to provide insight into the individual characteristics within different households which are likely to influence the success of energy management through water demand management. It is intended that this information can then be applied to enhance accuracy in modelling at a broader, more representative scale. All households considered in this study are detached dwellings, and it is likely that multi-residential dwellings will display different water and energy use characteristics.

5.5. Conclusions

Water demand management, through changing the duration of showers, reduced energy demand for all households modelled. By reducing shower duration to four minutes per shower (from between six to ten minutes), the reduction in energy demand across the five households studied was between 0.1 and 3.8 kWh p^{-1} d^{-1} (or 9% to 63% of baseline use). Given that the energy use for water service provision in Melbourne is approximately 0.3 kWh p^{-1} d^{-1}, such household energy use reductions through water demand management may offer a significant opportunity to limit the energy footprint of water service provision.

Household characteristics influence the efficiency of hot water system types in the households studied. For gas powered hot water systems, continuous type systems are more efficient in lower flow shower (4.4 – 6 L min^{-1}) households, whereas storage type systems are more efficient in households with higher flow (9 -10 L min^{-1}) showers. This is due to trade-offs between energy conversion efficiency losses and storage heat energy losses, both of which comprise a significant proportion of total hot water system energy use (33% to 36% for gas continuous systems, 19% to 22% for gas storage). As the efficiency of fittings and behaviours increases, energy losses from storage hot water systems increase in importance (i.e. storage losses represent a higher fraction of total water-related energy, as they are relatively fixed and don't scale down with reduced usage). Consequently, for storage type hot water systems the selection of an appropriate storage volume is important.

In response to shower duration demand management, savings in combined water and energy cost across the five households studied was \$37 to \$500 hh^{-1} y^{-1} (4% to 31% reduction from baseline). For a scenario in which electric storage systems were installed, energy cost savings would be more significant than for gas systems, at \$39 to \$900 hh^{-1} y^{-1} compared to \$5 to \$268 hh^{-1} y^{-1} for gas storage systems and \$14 to \$315 hh^{-1} y^{-1} for gas instantaneous systems (due to higher variable tariffs for electricity than natural gas, \$0.2678 kWh^{-1} vs \$0.0625 kWh^{-1}). Households with electric storage hot water systems may therefore have greater financial incentive to participate in water-related energy demand management (assuming similar tariff structures).

6. <u>The transition to improved water-related energy management: enabling contexts for policy innovation</u>

6.1. Introduction

Energy consumption related to water end use in Australian cities accounts for 10% of primary energy use per person, and approximately one third of this amount occurs in households (Kenway et al. 2013b). Improving the management of both water end use and energy end use has been a focus for policy and regulation, but this management effort to date has typically focused on water and energy as distinct issues. The influence of water use on energy use has not been a direct focus of policy or regulation in Australia. As a consequence, opportunities for water use management to assist with energy management have not yet been realised.

This chapter explores the potential for improved policy and regulation with a direct focus on household water-related energy (WRE) management in urban Victoria. It responds to a growing body of literature detailing the physical links between water and energy use in households, and consequent opportunities for improved management, by asking the questions:

1) Who are the key stakeholders with an influence on water and energy end use in households, and for what reason (objective) and how (mechanism) do they exert this influence?
2) For these stakeholders, what have been the key enabling factors in past experiences of policy innovation, and what strategies have been employed?
3) What are the views of these stakeholders on potential policy change for improved household WRE management, in particular the opportunities presented by a WRE policy integration focus (and likely barriers to the same)?

The aim of this paper is to highlight the medium-term work required to create an enabling environment for policy practitioners in Victoria to improve management of WRE use in households. By highlighting the experiences and perspectives of key actors within the existing institutional landscape, the work attempts to draw out the synergies and tensions within WRE management in relation to the work of policy practitioners 'on the ground'. In doing so, this work aims to lay the foundations for a policy roadmap for achieving better integration in water and related energy management.

6.1.1. Background

Integration issues in water and energy policy have received increasing attention in literature, predominantly from a high level (international, national), with a focus on examples in Australia and the US. Key findings in this literature have noted issues around fragmentation in water and energy decision making. The continued separation of water and energy policies was noted as a key challenge for effective management of water industry greenhouse gas emissions, in a systematic literature review of energy use in the water sector by Rothausen and Conway (2011). This analysis is supported by the work of King et al. (2013), who note the diversity of roles and agencies in both water and energy management as a challenge for water-energy policy coherence, compounded by differences in hierarchies for policy making between the sectors (namely, top-down for the energy sector, and some bottom-up features for the water sector). Authors in several countries, including Australia and the US, have recognised inconsistencies and opposing tendencies in water and energy management approaches (Hussey and Pittock 2012, Scott et al. 2011), stemming from a separation between the fields of environmental management, policy and regulation, and commercial water supply and wastewater treatment (Rothausen and Conway 2011). A need is identified for stronger cooperation and consistency between environmental targets, water supply strategy, energy efficiency and climate change policy (Rothausen and Conway 2011). To support this, analysts have highlighted that environmental policy needs to be capable of evaluating and integrating policy measures across sectors (Pittock et al. 2013). Examples of well integrated, coherent energy-water policies are lacking, with a corresponding need for coordination in planning and in allocation of responsibilities (King et al. 2013). It is also noted that the need for institutional change is likely to be ignored or resisted by key actors with power under current arrangements (Teschner et al. 2012).

In summary, the water-energy policy problem involves multiple actors, at multiple levels, with a diversity of interests. Efforts to achieve integration in water-energy policy need to recognise the complexity of these structural issues, and any methodology applied to further the case for improved WRE management will need to be capable of addressing them. The literature on transition management for socio-technical systems offers some guidance in this context.

6.2. Conceptual framework

Processes of institutional change have been the subject of study in the field of transitions theory. In a policy context, transitions theory focuses on pathways toward 'radical or fundamental change in government policy or public policy' (Huitema and Meijerink 2010). Institutional change is also a core focus of the field of institutional entrepreneurship, which deals with the contribution of various actors in leading or mobilising institutional change or policy innovation (Leca et al. 2008).

This paper draws on both fields. To understand how to facilitate a transition towards policies focused on improved WRE management, this study focuses on identifying enabling conditions for institutional entrepreneurship (or policy innovation) by key actors.

6.2.1. Socio-technical systems, transitions theory and transition management

Water and related energy use involves an interdependence of technical infrastructure and management systems, with both supply and user components, and multiple actors. As such, WRE use can be conceptualised as a **socio-technical system**. Conceptualising WRE use as a socio-technical system is a useful lens through which to approach WRE management, in that it accounts for relationships between supply and demand characteristics, multi-actor processes, and the inter-relatedness of technical and non-technical characteristics. Socio-technical systems are defined as clusters of elements, including technology, regulations, user practices and markets, cultural meanings, infrastructure, maintenance networks and supply networks (Geels et al. 2004). Changes in a socio-technical system involve not only changes in components, but changes in the structure of the system as well. Geels et al. (2004) note that an advantage of a socio-technical systems focus is in highlighting the inter-relatedness of supply and demand characteristics, and a focus which is wider than just one industry or sector.

A shift towards improved management of WRE use can therefore be conceptualised as a **transition** in a socio-technical system. The field of transition theory is concerned with the study of transitions, defined by Loorbach et al. (2010) as "long-term fundamental changes (irreversible, non-linear, multi-levelled and systemic) in the cultures (mental maps, perceptions), structures (formal institutions, and infrasystems), and practices (use of resources) of a **societal system**". Loorbach et al. (2010) note that transitions theory has been applied to socio-technical systems, innovation systems, and complex adaptive systems, all of which have several basic characteristics in common: (a) open systems embedded in an external environment, with which they co-evolve; (b) the changing external environment influences these systems; and (c) non-linear changes in system structure are evident in adapting to changes in the external environment.

Transitions in socio-technical systems are commonly explained through the ‘Multi-Level Perspective’ (the MLP) first described by Geels (2002). The MLP describes interacting processes in a socio-technical system, between the micro-level (the ‘niche’ level), the meso-level (the ‘regime’), and the macro-level (the ‘landscape’). Niches are embedded within regimes, and regimes within landscape. These are illustrated in Figure 15 (Geels 2012). The core concept of the MLP is the socio-technical regime, defined by Loorbach et al. (2015) as “a coherent, highly interrelated and stable structure at the meso-level characterised by established products and technologies, stocks of knowledge, user practices, expectations, norms, regulations, etc.” At the micro-level, socio-technical niches are the “locus for radical innovations”, protected spaces which act as “’incubation rooms’ for radical novelties” (Geels 2006). The macro-level of the MLP is the socio-technical landscape, which encompasses the wider exogenous environment (e.g. environmental problems, cultural attitudes, economy) which is beyond the direct influence of actors in the regime, but which affects socio-technical development (Geels 2006). New approaches emerge from niches in response to problems in the existing landscape and regime, and become available for uptake, diffusion and stabilisation at the regime level (given suitable conditions). A newly configured regime may then further influence the broader landscape factors. These interactions between niches, regimes and landscapes describe the ‘transition’ process in socio-technical systems.

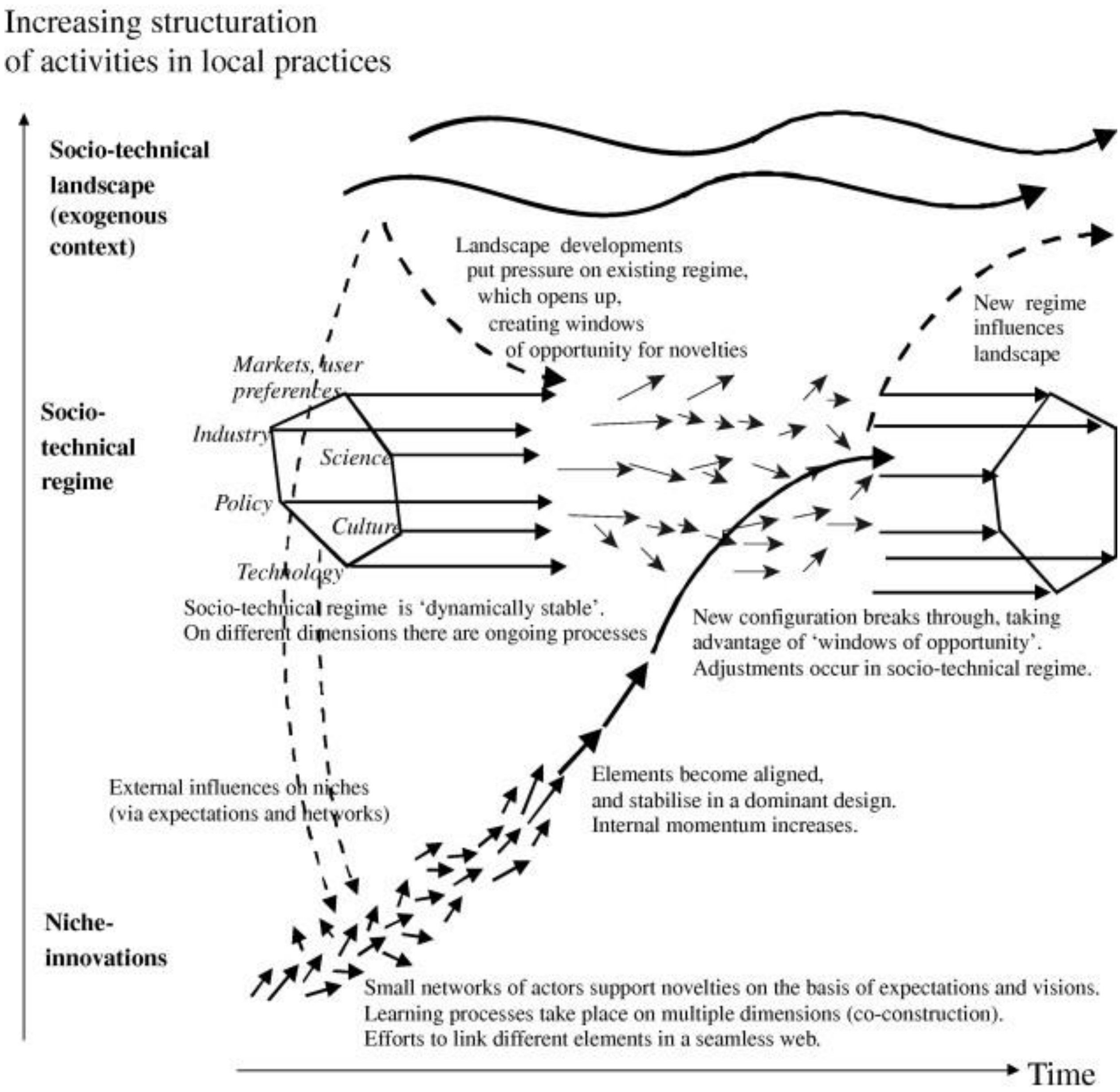

Figure 15: The multi-level perspective (MLP) in socio-technical transitions (from Geels (2012))

While transitions theory is concerned with the general study of change processes in socio-technical systems, the field of **transition management** is concerned with understanding how actors might influence this development to "attain desirable social objectives and avoid serious pitfalls" (Meadowcroft 2009). Transition management therefore provides a useful lens through which to approach a shift in water and energy management in urban households towards improved management of WRE use. Concepts in this field have roots in systems theory, evolutionary economics and integrated assessment. Transition management concepts can be employed to gain insight into how to "formulate governance principles, methods and tools to deal more systematically with fundamental system change" (Loorbach et al. 2010), and have frequently been applied to the problem of sustainable development (e.g. Bettini et al. (2015) Loorbach (2010), Meadowcroft (2009), Rotmans and Loorbach (2006), Smith and Stirling (2010), Smith et al. (2010)).

Transition management comprises several key components (Meadowcroft 2009): a transition dynamic, involving movement from one equilibrium to another; conceptualisation using the MLP; the use of future-focused visioning and goal setting devices (goals, visions, pathways and intermediate objectives); a focus on practical activities (arenas and experiments); and an emphasis on decision making under conditions of uncertainty, involving gradual adjustment of development pathways in line with long-term goals.

The conceptual framework of transition management faces a number of challenges:

- Practical challenges
    - There are practical challenges in developing inter-organisational collaboration and shared vision. Markard et al. (2016) note the highly uncertain nature of transitions processes, noting that "even the formulation of a policy problem is ambiguous and contested, let alone policy goals, strategies and expected outcomes."
- Theoretical challenges
    - Transitions academics have highlighted a dominant focus in the literature on the way in which change is stabilised and normalised at the regime level. They argue that a knowledge gap exists in understanding the interaction between niches and regimes through a transition, which produce new forms of governance (Bettini et al. 2015, Markard et al. 2012, Voß et al. 2009). It is further argued that an understanding of institutional context underlying societal transitions can assist in addressing this gap (Bettini et al. 2015).
    - Some critics suggest that transitions literature tends to focus on a 'teleological' treatment of successful transitions (Berkhout et al. 2004), without taking into account those that did not achieve success.

6.2.2. Institutional entrepreneurship

Institutions are "enduring patterns of social practice" (Hughes 1936) within our society which are maintained by formal and informal social constraints (e.g. rules, habits, constitutions, laws, conventions) (Khalil 1995). These constraints affect the behaviour of actors and organizations, or the "agents… that have preferences and objectives" (Khalil 1995). Organizations thus interact with each other and broader society within an institutional landscape, which influences their behaviour. In the context of water and energy use in cities, institutional analysis provides a way of conceptualising the way in which patterns have developed in society to manage water and energy provision and use.

The role of actors in influencing institutional change is the focus of studies in institutional entrepreneurship. In particular, institutional entrepreneurship focuses on “the activities of actors who have an interest in particular institutional arrangements, and who leverage resources to create new institutions or transform existing ones” (Garud et al. 2007). The field of institutional entrepreneurship contrasts the normally stabilising effects of institutions, which reinforce continuity and reward conformity (Garud et al. 2007), with the creative effects of entrepreneurial activities in seeking to bring about change within those institutions and/or organisational processes. This tension between effects of stabilisation and the pressures for change is referred to in literature as the ‘structure – agency paradox’, which explores the way in which entrepreneurial actors can be embedded within the stabilising structures of institutions, while also being able to ‘step outside’ their social context and act with the resources and motivation required to change those structures (Garud et al. 2007, Leca et al. 2008). Resolution of this paradox is necessary for institutional entrepreneurship to make an impact.

In a review of the institutional entrepreneurship literature, Leca et al. (2008) identify two broad issues as central to the study of institutional entrepreneurship: (a) the conditions under which an actor is likely to become an entrepreneur, and (b) the processes through which institutional entrepreneurship unfolds. They note that a number of studies suggest that ‘enabling conditions’ (Strang and Sine 2002) play a key role in institutional entrepreneurship, allowing resolution of the structure-agency paradox. They further note that the processes of institutional entrepreneurship which have received attention in the literature include the development of discursive strategies (i.e. framing an issue to highlight organisational failings and to justify change (Dacin et al. 2002, Greenwood et al. 2002, Maguire et al. 2004, Tolbert and Zucker 1996)), and the mobilisation of resources to develop those strategies for improvement (Leca et al. 2008).

The role of *enabling conditions*, and the processes of *resource mobilisation*, in institutional entrepreneurship as identified by Leca et al. (2008) have been adopted as a central focus for this work. The implication is that to begin a transition towards improved WRE management, niche actors will need to engage in institutional entrepreneurship to put forward new practices and approaches for adoption and stabilisation at the regime level.

6.2.3. Aim and objectives of study

Transitions theory focuses on the *uptake and stabilisation* of new practices, norms etc. within an institutional field or regime (the institutional field or regime being characterised by a collection of actors who share norms, etc.). This paper takes the view that for household WRE management to become a stronger focus for policy, a transition will be required away from current separate management approaches for water and energy use towards a more integrated approach. Such a transition is a long-term process (perhaps 20-50 years). The essential precursor steps in this process – in which new practices emerge and become available for adoption at regime/ field level – have received little attention in transitions literature. Transition management academics have highlighted a knowledge gap arising from the limited attention given to understanding how niches and regimes interact through transitions, and thereby produce new forms of governance (Bettini et al. 2015, Markard et al. 2012, Voß et al. 2009). This paper argues that, if we wish to better manage transitions, intervention at this 'niche emergence' level offers greater opportunity to influence the direction of transitions, by creating favourable conditions for emergence. Furthermore, a focus on the creation of favourable conditions for niche emergence is likely to assist subsequent adoption and stabilisation processes at regime level, by focusing on decision contexts for multiple key actors and thereby laying the groundwork for building consensus.

The particular focus of this paper is on the shorter-term ways in which key actors might begin to initiate change towards household water-related energy management, as a foundation for a longer-term transition. The field of institutional entrepreneurship will be drawn upon to explore the ways in which such change are being initiated. To achieve this, this paper seeks to understand the perspectives of key actors within the current institutional landscape. In particular:

- Who are the key stakeholders with an influence on water and energy end use in households, and for what reason (objective) and how (mechanism) do they exert this influence?
- For these stakeholders, what have been the key enabling factors in past experiences of policy innovation?

  What are the views of these stakeholders on potential policy change for improved household WRE management, in particular the opportunities presented by a WRE policy integration focus (and likely barriers to the same)?

6.3. Methodology

6.3.1. Participant selection and recruitment

Participation was sought from organisations with an interest in the management of water or energy use in households in urban Victoria, with a primary focus on participants with supply side management interests. Consumers and households were not engaged in the study (however a participant in a consumer protection policy role was included in the study). Participants were initially invited to participate in the study directly by the researcher, via phone or email, through relationships established at stakeholder workshops in earlier stages of the parent research project. The ‘snowball’ method (Robson 2002) was then used to identify further participants of relevance to the research, upon recommendation from the initial participants. These were contacted through introduction via the recommending party.

Participants included those with an active role in influencing water and/or energy use in households, in addition to parties significantly interested in or affected by household water and/or energy use but without a direct pathway of influence on the households themselves. A range of organisations and individuals were contacted which included water utilities (bulk and retail), energy distribution and retail companies, state government departments, local governments, independent regulatory bodies, community organisations, and industry professional organisations. These participants were principally from the water sector, energy sector, and residential building sector, in addition to the social and environmental sectors. Participants are not a representative list of all influences, but were selected to highlight the diversity of key influences and their perspectives.

Study participants are outlined in Table 22.

Table 22: List of interview participants

ID	Organisation	Position Title
A	Local government greenhouse emissions management network	Chief Executive Officer
B	Water utility (retail)	Manager, Strategic Communications
C	Water utility (retail)	Manager, Demand Forecasting
D	State government environmental sustainability organisation	Specialist, Energy Efficiency
E	Water utility (retail)	Manager, Strategic Projects

ID	Organisation	Position Title
F	Local council	Senior Advisors, Environmentally Sustainable Design
G	Non-government social welfare organisation	Manager, Policy and Research
H	Energy infrastructure business (gas)	Manager, Asset Planning
I	Not-for-profit climate change management organisation (community focused)	Program Manager, (emissions reduction program)
J	State government department	Policy Officer, (energy efficiency incentive scheme)
K	Water utility (retail)	Specialist, Greenhouse Gas and Energy
L	State economic regulator	Policy Supervisor, (energy efficiency scheme)
M	Industry-led training centre for sustainability in trades	Chief Executive Officer
N	Not-for-profit sustainable living organisation	Senior Energy Analyst
O	State government department	Senior Policy Officer, Water and Catchments (Policy, Governance and Legislation)
P	Independent professional - Building regulation sector	Experienced Regulatory Officer
Q	Water utility (bulk)	Principal, Integrated Planning

6.3.2. Interview process

Interviews were conducted between July and October 2017, in person (15) and over the phone (2). Each interview was between 45 minutes and 1 hour in length and was audio recorded. Where required, short follow-up phone calls were made to gather supplementary information to clarify interview responses.

Interviews were semi-structured, and were conducted by the researcher as an open conversation with the participant. Interview participants were presented with outcomes of the research expressed in Chapters 4 and 5 of this thesis, following which a list of questions was then used to guide the interview process towards topics of interest. These questions were adapted to suit each participant, and questions were included or excluded as appropriate to the participant's role and experience. The interview questions focused on each participant's role, professional relationships, experience of strategic planning processes, experience of change in work direction/priorities, and perspectives on the potential for WRE management in households.

A schedule of the questions used to guide interview discussion is provided in Appendix A.

Audio recordings of the interviews were transcribed by the researcher, and thematically analysed according to methods outlined in Section 6.3.3 below.

6.3.3. Transcript data analysis

6.3.3.1. Theme 1 – key stakeholders influencing WRE use, and their roles

During the interviews, participants were asked to describe the role of their organisation. These responses were analysed, in conjunction with a review of grey literature focused on organisational mission statement and objectives (e.g. organisation or department charter, annual reports, statements of obligations).

The above data was then analysed to identify organisational (a) objectives, and (b) mechanisms with relation to management of water or energy end use, according to the following definitions:

- *Objective*: the outcome an actor is seeking in influencing the system relating to water and/or energy use in households. Objectives were summarised into the following three categories, which were drawn from groupings observed in participant responses:
    - Technical: Security and reliability of water and/or energy supply
    - Environmental: Strategic resource management, including GHG emissions management and water use efficiency
    - Social: Social welfare, including cost of living and liveable communities
- *Mechanism*: the type of activity undertaken to exert influence on water and/or energy use in households. Examples include: end-user education to influence behaviour; development of standards; regulation; provision of economic incentives.

Stakeholders were also grouped into two broad categories to aid in discussion of results: (a) those with a direct influence on water and/or energy end use within households, (b) and those with a clear interest but an indirect influence.

6.3.3.2. Theme 2 – past experiences of successful policy innovation

During the interview, participants were asked to describe a past experience in their work where they have observed or been part of a new policy direction. These past experiences described by the participants could relate to a new policy direction in any aspect of their role, and did not necessarily need to relate to water and/or energy use. The focus of the question was on experience of change processes.

Analysis of responses focused on the role of enabling conditions and processes of resource mobilisation in institutional entrepreneurship activities, as identified by Leca et al. (2008) (described in Section 6.2.2). Interview transcripts were coded to identify the following factors (Leca et al. 2008):

- Enabling context:
    - Field-level conditions
        - Precipitating jolts or crises, e.g. social upheaval, technological disruption, competitive discontinuities, regulatory changes
        - Acute, field-level problems which might precipitate crises, e.g. scarcity of resources
    - Individual-level conditions: organisational internal leadership, organisational culture
- Resources mobilised:
    - Intangible resources
        - *social capital*: position in a web of social relations that provide information and political support, and ability to draw on that standing to influence others' actions
        - *legitimacy*: the extent to which an author's actions and values are viewed as congruent with values and expectations of greater environment
        - *formal authority*: legitimately recognised right to make decisions
    - Tangible resources – financial assets, information, skills and expertise.

6.3.3.3. Theme 3 – perspectives on improved household WRE management

Participants were talked through the research outcomes presented in Chapters 4 and 5 of this thesis (Binks et al 2016, Binks et al 2017). They were then asked to comment on the relevance to their work (if any), their views on what opportunities they saw WRE management presenting (generally, not limited to their work), and what barriers might need to be overcome. Responses were grouped according to common themes, and summarised.

6.4. Results

6.4.1. Theme 1 – Who influences household WRE use, why and how?

Stakeholders with both direct and indirect influences on household WRE were interviewed. Management objectives spanned greenhouse gas emissions management, water supply security, water efficiency, water and energy supply reliability, cost of living and social welfare. These objectives were achieved through mechanisms such as expert advice, information and training, advocacy, economic incentives, economic regulation and building regulation.

6.4.1.1. Direct influence on household end use

Energy sector stakeholders having a direct influence on household end use were interviewed, including not-for-profit organisations (I, N), and government-run sustainability bodies (D) and energy efficiency incentive schemes (J). The objectives of these stakeholders in engaging with household end use issues focused on greenhouse gas (GHG) emissions management (D, I, J, N), and cost of living issues relating to energy use (D, I, N). The mechanisms employed to achieve these objectives included the provision of expert advice (I, N) and economic incentives (J) to influence technology choice, and provision of information to improve understanding of energy use issues and impacts (D, I, N). These stakeholders had a strong focus on influencing technology choice to achieve GHG emissions management objectives.

Water sector stakeholders interviewed with a direct influence on household water use included a water supply entity (BCE), and a state government water efficiency regulator (O). The objectives of their work of relevance to household end use were focused on water supply security and cost of living. Mechanisms for achieving this focused primarily on provision of information targeting user behaviour (BCE), and rebates to encourage water-efficient technology uptake (O).

Stakeholders from the residential building and building services sector were interviewed, comprising local and state government regulatory actors (F, P). The objectives of these stakeholders in engaging with household end use issues focused on environmental protection in the form of GHG emissions management (F, P) and water efficiency (P), and social welfare in the form of liveable communities (F). Regulation of physical features of residential buildings (new or renovated) was employed to achieve these aims.

6.4.1.2. Indirect influence on household end use

Stakeholders interviewed with a clear interest in but an indirect influence on household end use issues included a non-government emissions advocacy network (A), a non-government industry skills body (M), an energy distribution entity (H), a non-government social welfare organisation (G), an energy sector regulatory body (L), and a bulk water supply entity (Q) Their interests in household end use issues included GHG emissions management (A, M), protection of affordability of essential services for households (G, L), and maintaining reliability of energy (H) and security of water (Q) supplies. This was achieved through influences such as advocacy (F, G) and provision of expert advice and training (A, M) relating to renewable energy technologies and energy management opportunities and strategies. Other influences included research and strategy development to drive water efficiency (Q) through water retail entities, economic regulation (L) of energy pricing and efficiency incentive schemes, and economic influences such as energy tariff setting (H).

6.4.2. Theme 2 – past experiences of successful policy innovation

Stakeholders recounted past experiences of policy innovation under a number of field-level (i.e. among organisations and/or agencies concerned with similar services or products) and individual level conditions. Field-level conditions included changes in government policy/priorities, technological/market disruption, development of industry norms and community attitudes. Individual level conditions included organisational leadership, and a strong sense of organisational role within the community.

6.4.2.1. Field-level context

Change in government priorities and/or specific new government policies were the most common field-level conditions referenced as underpinning policy innovation (B, D, E, J, K, M, N, P, Q). Shifting policy priorities following a change of state government were noted as instrumental to new energy-related policy initiatives in both the energy sector (D, J, M, N, P) and water sector (K). These came about as a response to an increased federal government focus on emissions (D, M, P), followed by a shift of state government priorities to a focus on cost of living concerns in with a change in state political leadership (J, N). In terms of specific government policies, the state government Water for Victoria strategy was referenced by participants in the water industry (B, E, Q) as providing impetus for initiatives beyond the scope of traditional water sector operation. Similarly, a new state government water efficiency strategy was also noted (Q) as underpinning new approaches to cost-benefit analysis of water efficiency programs.

Technological / market disruption was noted by energy sector stakeholders (A, D, I, J) as a key factor in policy innovation. This was noted in examples of policy formed in response to increasing solar PV penetration disrupting energy markets, increasing cost of energy, and rapid population growth changing residential development profiles. In case A, the disrupted nature of energy markets was seen as an opportunity to participate in distributed energy generation activities to both safeguard against growing costs and to further greenhouse gas emissions reduction goals (the purpose of the organisation). Rapid population growth and corresponding growth in greenfield development was leveraged as an opportunity for targeted residential energy efficiency initiatives (D). The intersection of growing energy cost concerns and increased availability of battery storage was seen as an opportunity for medium-scale rooftop solar PV programs in a highly developed area (I). Similarly, growing energy cost concerns provided impetus for a residential energy efficiency program (J).

The development of industry norms was also noted as a driver for policy innovation, by stakeholders in the residential building regulation and energy sectors (F, H, P). Emergence and maturation of environmentally-conscious planning approaches to regulation of residential development were cited as a driver for new council policy (F). Similarly, changes in the national construction code were noted as underpinning changes in state regulation (P). New risk-based asset management standards developed by the peak energy industry regulator were also noted as a trigger for changes in asset renewals approach in energy the distribution sector (H).

‘Green’ concerns held by local council constituents were cited as a supporting factor in development of new sustainability policy for regulation of residential development (F).

6.4.2.2. Individual-level conditions

Leadership was noted as an important factor in case BCE. Stakeholders from a water sector entity highlighted strong leadership from their CEO in setting a vision and mandate for ‘breakthrough performance’. This was accompanied by deliberate training and soft skills development within the organisation to build the capacity of staff to innovate. This created an environment in which staff felt empowered to innovate.

Sense of the role within community was also referenced as a factor driving innovation. A local government body (F) emphasised the importance of their role in ensuring a liveable community, driving policy innovation for regulation of residential development. Similarly, a water sector entity highlighted the extent of their influence in the community as a force for change, and noted this as a driving force behind policy innovation extending their role beyond a water-only focus to further the goal of ‘best community value’ (BCE).

6.4.2.3. Resources mobilised in innovation

In recounting past experiences of successful policy innovation, stakeholders interviewed highlighted a range of resources mobilised to achieve their innovation aims. Resources mentioned included authority, legitimacy, and social capital, in addition to more tangible resources such as information and expertise.

Authority (i.e. the legitimately recognised right to make decisions) was mobilised in the forms of (a) authority conferred by the role of the actor or their organisation, and (b) direction by state government Minister. Examples of the former included the creation of a new energy and GHG-focused position within a water sector entity (K), the creation of a new planning policy within local government (F), a shift in asset renewals approach by an energy distribution entity (H), and development of a new approach to accounting for the economic benefits of water efficiency (Q). The ability to leverage authority to innovate in response to changing context was provided in all cases by the fact that the role of each actor was formally recognised as having the power to make such decisions (i.e. water network management, local government planning regulation, energy network management, and water security planning). In case P, advocacy by the stakeholder was successful in eliciting direction from the responsible state government Minister to support changes to residential building regulation.

Legitimacy (i.e. actions congruent with expectations of greater environment) was also leveraged in a number of cases. This was noted in the form of action in line with community expectations expressed through local council (F, I), and through consultation with industry networks supported by transparent and accountable decision making processes (J).

Social capital was leveraged in a several cases. Networks played a strong role, including inter-organisational knowledge sharing and collaboration (I, A, M), stakeholder engagement (F), and the building of cross-sector alliances (B). A local government actor noted the development and provision of a free tool for industry practitioners (particularly vulnerable / low skill stakeholders) as important in building trust and support for new policy (F). This was coupled with relationship building and consultation with key industry stakeholders to understand and address concerns, building transparency and trust to support new policy. The sharing of research outcomes and information between networks was particularly important for non-government actors (A, I, M), used as an evidence base to underpin new policy approaches. A water sector entity (B built on their standing as an actor with strong community relationships to build alliances with other essential service providers (telecommunications, energy), driving new approaches to integrated service delivery.

Tangible resources leveraged included skills and expertise (J), and information exchange. Two stakeholders in government entities referenced the importance of expertise in their ability to anticipate external trends and pro-actively develop policy ‘in the background’, to be ready when external context (e.g. government priorities) opened up opportunities for action to innovate.

6.4.2.4. Strategies for mobilising resources

Strategies employed by stakeholders in instigating change included a focus on flows of information, including the commissioning of expert consultant research and advice, internal education, and advocacy and networking.

Research and expert advice sought (D, I, Q) took the form of economic studies on the expected impact of technology change (e.g. solar PV, battery storage) in households and businesses. These included studies on the potential costs and benefits for households (D), and capital cost affordability issues (I). Economic studies were also undertaken to support cost-benefit studies for water efficiency strategies, by defining the economic value of water retained in storages (Q). Sources of external research and expert advice included consultants, and research partnerships with universities.

In addition to the commissioning of external research, ongoing internal research was also employed (D, J, N) to gather information on emerging trends. These included residential sector trends and technology availability (D), and emerging social issues such as energy hardship and increasing gas prices (J). Internal research was also employed to better define the impacts of household energy access and use on health and wellbeing (N). Outcomes of such internal research were employed to forecast emerging opportunities in the external environment and focus the development of new policy initiatives. Internal education was also employed by multiple stakeholders (D, I) to build technical capability around emerging technologies, impacts and potential solutions.

Several stakeholders (A, D, P) engaged in advocacy and networking (A – membership; D - state government budget and strategy processes; P – key decision makers) to garner support for their initiatives. This included building connections between key decision makers to aid integration in urban planning (i.e. energy networks planners and town planners) at critical design stages (A), and advocacy to members/constituents (A). State government strategy and budget development processes were also targeted (D), through provision of expert advice (drawing on research, and highlighting past successes). Relationships with powerful decision makers were leveraged to garner support for policy initiatives (P).

6.4.3. Theme 3 – perspectives on improved household WRE management

6.4.3.1. Perceived opportunities in water-related energy management

Respondents noted opportunities in WRE management in several distinct activities, including (i) consumer education and advocacy, (ii) development of standards, (ii) opportunities for participation in electricity networks and markets (including distributed generation), and (iv) reframing organisational boundaries.

Consumer education and advocacy was raised primarily in the context of behaviour change in water end use activities (B, D, F, I, J, O) and technology choice (H, D, F). Several participants were of the view that the energy impacts of water use are currently poorly understood and that consumers generally lack awareness of the water-energy linkage, and therefore consumer education would be beneficial to inform better consumer choices. Addition of energy savings information was noted as likely to be beneficial in bolstering water saving arguments. It was suggested that campaigns linked to price/affordability and ‘gas shortage’/energy crisis issues are likely to be more potent drivers than efficiency, as these issues are currently highly politicised and more relevant for consumers. A key barrier to the success of education and advocacy approaches was noted in the absence of a strong ‘crisis’ (such as a drought) to drive action – it was suggested that greenhouse gas emissions and climate change impacts are too abstract to motivate behaviour change. Affordability and gas shortage were therefore suggested as likely more effective motivating ‘crises’. Another barrier noted, however, was the short-term benefits of behaviour change impacts on affordability, as distributors and retailers would likely respond to reduced revenue by raising fixed tariffs to cover their costs. Equity issues were also raised in relation to full volumetric charging approaches, with low-income and vulnerable houses likely to have less control over quality of housing and appliances (due to tenancy issues and capital investment required for new stock).

Standards were put forward as an opportunity to influence the design phase of residential buildings, which was seen as a significant gap in current WRE management. Several participants (F, L, H, M, N) noted that many of the most significant opportunities to influence WRE use were in the selection and layout of building services, but that the impact of this is not currently considered or actively designed for. Furthermore, a key barrier to better selection and design of building services was noted in the separation of CAPEX and OPEX impacts – with developers/builders making key decisions which would affect the long-term OPEX of residents, but with no incentive to design for operational efficiency as OPEX does not impact them; but instead driven in design choice by CAPEX considerations only. (Similar issues exist in the landlord/tenant divide). It was suggested that plumbing and building standards, building codes and development approvals (including associated scorecard tools) could intervene to target this issue more specifically.

Standards were also proposed in relation to consumer information, in the form of standardised requirements for information on WRE use in consumer bills (H).

The third key opportunity raised was the ability to participate in electricity markets (A, E, K, L, N). A push towards all-electric homes was an issue frequently raised (E, K, L, N). This shift is anticipated due to the increasing prevalence of grid-connected renewable energy sources (e.g. solar, wind) both before (i.e. in the network) and behind the meter (i.e. household), which will make electricity less greenhouse gas intensive than natural gas and likely more economic in the context of recent gas shortages in Victoria. The potential for water systems to aid in peak load management and network stabilisation was raised, by using hot water systems as battery energy storage to smooth household demand (A, K, L, N) and to stabilise energy networks (L, K, N). The rising trend in 'internet of things' type management of household appliances was highlighted as a key enabling factor in these management approaches, relating to the all-electric home trend. The potential for excess household PV energy generation to be on-sold/transferred to water utilities for use in energy intensive manufactured water (e.g. desalination) was also noted (E, see paragraph below for detail). Further, one respondent (K) highlighted the possibility of water utilities partnering with energy distributors to use water networks as energy network storage (e.g. pumped hydro) to assist with energy network stabilisation.

Stakeholders also highlighted opportunities at the macro level, in the form of shifting system goals or paradigms (E, G). Both stakeholders challenged traditional approaches to defining the 'value' of policy outcomes in water and energy management. Stakeholder E noted that WRE use was not in itself a problem, but rather the fact that the energy being used contributes to GHG emissions; similarly, with the advent of alternative supplies such as desalination, water use may not necessarily need to be as constrained for water security purposes if such alternative supplies are generated using renewable energy sources. This stakeholder put forward the possibility of a water utility investing in urban development, by engaging in installation and management of distributed renewable energy generation (such as rooftop solar PV with battery storage) in new residential developments. Ownership and management of the energy source would allow the water utility to access renewable energy to run increasingly energy-intensive water supplies, while simultaneously providing low-cost energy to the to the community. This stakeholder argued that pursuit of such approaches would require decision making on a basis of seeking 'best value solutions', as opposed to traditional 'least cost solutions'. Existing examples of similar undertakings by other water entities were provided, including investment in the development of parklands in a disused water infrastructure corridors to contribute to both community amenity and water quality protection, which was undertaken in response to community priorities following Ministerial approval. The stakeholder interviewed (E) highlighted that under current arrangements, such approaches challenge state government economic regulation given that these activities fall beyond the regulated mandate of water utilities, and require explicit sign-off from the responsible government Minister. It was noted that the peak industry body for water supply services is in the process of developing papers on value, exploring whether water corporations should be expanding their value proposition beyond core water and sewer services, and that the recent state water strategy (Water for Victoria) supports a 'shared value' approach.

6.4.3.2. Perceived barriers to water-related energy management

Stakeholder views on likely barriers to WRE management included (a) complexity challenges, (b) fragmented institutional arrangements, and (c) lack of a strong common 'crisis' to motivate consumer behaviour change.

Complexity challenges were raised in the context of information needs, and skill requirements. The lack of quality available water-energy end use data was raised by several stakeholders (D, L, M). It was noted that fragmentation of water-energy responsibilities results in a lack of 'critical mass' on the part of any one stakeholder with respect to motivation to take the lead on research into cross-cutting issues (M, Q). Motivation aside, stakeholders highlighted the complexity of gathering such data and the corresponding cost issues, stemming from the fact that water and energy end use are typically the concerns of separate stakeholders, and consequently it can be difficult for a single stakeholder to justify increased time or costs associated with collecting data beyond the scope of their role (C, D, J, Q). The physical complexity involved in data monitoring for water-energy interactions was also noted as a significant factor driving costs of data collection for water-energy interactions (D). Such data challenges, set against the high level of data integrity required by existing energy savings incentives programs (such as Renewable Energy Certificates) to claim on the energy saved through water efficiency measures, was raised as a historically observed and continuing barrier to potential WRE management approaches (L).

Complexity issues were also highlighted in terms of the increased sophistication in skills required for policy-makers, industry tradespeople, and consumers to understand and manage combined water-energy impacts (F, G, L, M).

Fragmentation of responsibilities, and subsequent sharing of costs and benefits of WRE efficiency approaches, was highlighted as a barrier in a number of contexts: water and energy supplier versus end user roles; energy distribution networks versus energy retailer roles; and developer/landlord versus tenant roles.

Fragmentation between energy distribution and supply entities and the energy consumer was raised by an energy distribution network entity (A). They commented that although the outcomes of WRE management initiatives would benefit them (in terms of greater control over network demands), they did not have the direct relationship with the consumer required to engage in such approaches, and that the energy retailers with the necessary consumer relationships would see less benefit in the outcomes. Similarly, multiple stakeholders (B, C, G) highlighted the potentially mixed motivations for a supply entity to encourage end-use efficiency due to the likely impact of reduced revenue through volumetric charging.

Fragmentation in capital and operating expenditure and savings between property owners (developers, landlords) and tenants was highlighted as a likely barrier to WRE management approaches in residential design, construction and appliance choice (M, O). This was raised in relation to the end-user (tenant) receiving the longer-term benefits of water-related efficiency investments in terms of reduced water and/or energy operating costs, with the developer or landlord bearing the impact of the capital investment and likely no share of the operational savings. This issue is not unique to WRE management, and has previously been noted as a barrier to water and/or energy efficient design, but any increased complexity due to ‘water-related energy efficient’ design would likely exacerbate the issue.

Fragmentation in institutional roles was raised in the context of separation in water and energy management, leading to both lack of motivation and difficulty in justifying work beyond the core scope of a stakeholder’s role (C, D, J, Q), as discussed above under complexity challenges related to information needs.

Finally, the lack of a clear driver or ‘crisis’ focus for behaviour change was highlighted by several stakeholders as a potential barrier to WRE management (F, H, L). It was noted that in the experience of these stakeholders, efficiency arguments alone were not successful in motivating changes in consumer behaviour, and that successful examples had all been associated with a clear crisis such as a drought.

6.5. Discussion

6.5.1. Insights for water-related energy management policy

Shifts in government priorities and/or policy direction were noted most frequently by stakeholders interviewed as the contextual driver that facilitated examples of policy entrepreneurship. The importance of government-level shifts is echoed within stakeholder perceptions of potential opportunities in WRE management, with multiple respondents suggesting that any move towards greater integration of water and energy use management would need to be driven by state government (L, N, P). Three main reason were given: (a) state government is best placed to have a holistic view of cross-cutting issues across water-energy siloes, particularly with responsibility for water and energy issues falling under the same department in Victoria; (b) that state government would have the most interest in seeing solutions to cross-cutting issues (such as WRE) and consequently in creating an environment to implement those solutions (N); and (c) that state government has the authority to develop policies and set direction to create such an environment (P). Based on the past examples of successful policy entrepreneurship given by stakeholders, the kind of information which might support such a shift includes economic cost-benefit analysis of consumer impacts and analysis of trends in consumer and/or sector behaviour (D), and global/national trends in industry practice (P).

Consumer education was also highlighted by many stakeholders interviewed as a strong opportunity for WRE management. It was noted that water utilities are likely to have the strongest customer relationships (O), and are therefore well placed to drive such initiatives. Also important here is the perceived role of consumer /community attitudes and support as a key resource mobilised in past stakeholder experiences of policy innovation (e.g. stakeholders F, I). Increasing information flows and education for consumers has the potential to raise public awareness and understanding of WRE issues, which in turn has significant potential to shape community concerns, building a political resource which can be mobilised for entrepreneurship activities. This feedback loop (information – awareness – political concern) has the potential to lead to longer-term transition outcomes. However, stakeholders also noted that an essential condition for such an approach is the existence of a clear 'crisis' to drive consumer interest in engaging with information and education campaigns (F, H, L). In the absence of such a driver, success of information and education campaigns is likely to be limited. It was suggested that the recent 'gas shortage' crisis and growing concern about energy affordability could offer potential as motivating issues.

Finally, performance standards were also put forward as an area of opportunity by a number of stakeholders interviewed. Several noted that the building design stage is where consideration of operational water-energy impacts can be most influenced, and that there is currently a big challenge to overcome lack of integration of water/energy considerations in this design stage (e.g. location of hot water system with respect to end use water services). Building sector stakeholders (e.g. P, F) have a strong regulatory influence at this stage in the form of the building code, and residential development approvals, which address building design aspects. These stakeholders reported experience of policy innovation in the context of shifting government priorities (P), and development of industry norms (F). Information played a key role in the form of advocacy towards state government key decision makers based on global/national trends (P), as did the leveraging of strong social capital and legitimacy (F) (built through engagement and transparent processes).

Despite the current gap in integrated water-energy considerations in building standards and regulation, however, the building sector is seen as an area for achieving greater integration of water-energy considerations, with water and energy impacts both included in the same development approvals processes and building codes. This might be attributed to the ways in which the residential envelope itself drives considerations of operational resource use as a whole, as a function of the set of services provided within a residence. Thus an opportunity for improved WRE management may arise through further consideration of (a) an identified gap in consideration of integrated water-energy impacts, and (b) an existing confluence of water and energy regulation. This opportunity would assist in overcoming some of the barriers identified in the CAPEX/OPEX divide.

Complexity of data and skill requirements, and fragmentation of responsibilities, costs and benefits, were two of the most commonly identified barriers to progress in WRE management. Interaction between these issues was also highlighted, with fragmentation of water-energy responsibilities noted as a barrier to collecting the complex data required to account for water-energy interaction (due to an inability to justify increased expenditure on issues beyond the core focus of a water / energy / supply / use focused role). The development of benefits-sharing frameworks, and support for inter-organisational collaboration, may also have the potential to contribute significantly in this context.

6.5.2. Common goal-setting for transition management

A core principle of transition management is the setting of a common vision or goal to guide transitions. Those key actors with an interest in household WRE end-use who were interviewed for this project displayed a diversity of organisational goals and purposes. These spanned environmental protection, emissions reduction, resource efficiency, security of supply and consumer protection. In general, energy sector stakeholders showed a dominant focus on emissions reduction and consumer impacts (cost of living). By contrast, water sector stakeholders showed a dominant focus on security of supply and cost of living. Finally, residential building and building-services sector stakeholders were primarily motivated by GHG management and consumer resource efficiency, relating to residential amenity and cost of living. If a common goal was to be set for all these sets of stakeholders to guide a transition toward improved WRE management, a focus on consumer impacts could be a common issue of interest with the potential to achieve buy-in from stakeholders across these sectors. This might be achieved through a focus on cost of water and/or energy services (i.e. tariffs, or volumetric usage), or through a focus on consumer amenity (e.g. thermal comfort, water/energy 'productivity'). However, it was highlighted that there are potential disadvantages of a narrow focus on household costs solely by reducing consumer usage volumes. Stakeholder (G) noted that such approaches are likely to lead to backlash through upward market pricing pressures as water and/or energy suppliers seek to cover their business operating costs, and thereby perhaps undermine consumer financial outcomes in the longer term.

6.6. Conclusions

This study explored enabling conditions for policy entrepreneurship for improved water-related energy management. This was achieved through a focus on identifying the objectives of key stakeholders with regard to household water and/or energy management, and their past experiences of policy change contexts and resources. Stakeholder objectives were found to vary across sectors, but cost of living was a common theme, and may therefore offer a basis for developing a shared vision for a transition toward improved household WRE management. State government policy and/or priority changes were the most common context referenced as underpinning stakeholders' past experiences of policy innovation. Strategies which had been successfully employed for policy innovation focused primarily on flows of information, including cost-benefit analysis (both economic and non-economic cost), the identification of emerging sectoral trends, and advocacy and networking to garner support.

Key medium-term opportunities for household WRE management were noted by stakeholders in consumer education and advocacy around water-energy impacts, and the development of residential building standards to better manage the selection and layout of building services. These opportunities were seen to be tempered by several barriers in the form of complex information needs and skills required to understand water-energy impacts (for industry and consumers alike), and fragmented approaches to cost-benefit between (a) supply versus use orientation, (b) distribution of services versus retail supply, and (c) residential developers versus residents.

These findings suggest that to create an enabling environment for policy innovation for improved household water-related energy management, a focus on the following may be beneficial:

- Policy framing and data analysis focused on impacts of WRE use on household cost of living, as a unifying vision across key stakeholders and sectors;
- Advocacy to shift state government policy priorities to a clearer focus on integration of water and energy management considerations, or anticipation of emerging government priorities and the pre-emptive demonstration of the relevance of WRE management to those priorities;
- Collection of data to support cost-benefit analysis of the expected impacts of household WRE management policy, in both economic and non-economic (e.g. health and wellbeing) terms;
- Data analysis to support selection and layout of water and energy service infrastructure in residential buildings for improved WRE outcomes;

- Development of tools and materials to improve literacy in, and visibility of, household water-energy interactions;
- Development of 'shared value' frameworks to better distribute the costs and benefits of WRE management.

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7. <u>Discussion and conclusions</u>

7.1. Responses to the foundational hypotheses

In Section 3.2.2 of this thesis, I presented a ladder of hypotheses building towards a broader, long-term goal of integrated resource management (Figure *2*, Section 3.2.2). The scope of work undertaken for this thesis is framed by the three foundational hypotheses of that ladder, being:

i) There are ‘levers’ within households where water-energy interactions are most significant.

ii) There are pathways through which resource managers can influence water-related energy use in households.

iii) There is sufficient motivation / capacity for resource managers to engage in integrated water and energy management.

The work presented in Chapters 4, 5 and 6 contributes towards answering these hypotheses. This contribution is discussed in the following sub-sections of this thesis.

7.1.1. Hypothesis i): There are ‘levers’ within households where water-energy interactions are most significant

Significant variation in WRE between households highlights management potential

Chapter 4 presented a detailed description of the water and related energy use characteristics of seven individual households. Outcomes demonstrated that WRE use, and associated costs and energy-related emissions, can vary significantly between households. WRE use was observed to vary between the different households studied by between 2 and 7 kWh p^{-1} d^{-1}, representing 13% - 79% of household energy use. Furthermore, in the five Melbourne households studied WRE use was found to be responsible for 6% – 25% of GHG emissions for household energy consumption, and variable water and related energy costs comprised 23% - 55% of total household water and energy costs. Comparison of water use in the sample households against average Australian household water use demonstrated that the studied sample captures a broad cross-section of total water use characteristics. The significant variation demonstrated in WRE, and associated costs and emissions, between the households studied suggests that opportunity for management exists in intervening to influence the characteristics of households which contribute most to this variation.

Key end uses influence the magnitude of WRE use in households

Differences in WRE use (i.e. kWh) between individual households were found to be driven primarily by showering, hot water system energy losses, and clothes washer usage. If considering GHG emissions associated with WRE use, dishwasher and clothes washer usage drove the greatest variation between individual households. In terms of utility costs, showering and clothes washer usage contributed most to variation in water and related energy use costs between households. Interventions focused on these end uses - which drive the greatest variation in WRE use, and related costs and emissions between households – are likely to offer the greatest potential as ‘levers’ for WRE management.

Showers are a key point of influence across multiple WRE impact categories

It was demonstrated in Chapter 4 that showers are a particularly important leverage point for integrated water-energy demand management. This is because they represent a substantial and consistent direct contribution across all impact categories - to variation in household water use (14% to 67% total), WRE use (11% to 67% total), water and energy costs (11% - 59% total) and GHG emissions associated with household WRE use (5% - 36% of total). Indirectly, they also impact significantly on hot water system energy use and associated losses, which were shown to be the second most influential WRE end use category.

The potential for showering as a focus of WRE demand management was further explored in Chapter 5, in a case study exploring the range of potential energy use impacts of a shower water demand management program in the five Melbourne households studied. It was found that a shift to four-minute showers (from baseline durations of six to ten minutes) would reduce water-related energy demand in the households studied by between 0.1 and 3.8 kWh hh^{-1} d^{-1} (corresponding to 30% - 1000% of the energy required for water service provision, estimated at 0.3 kWh p^{-1} d^{-1}). This would correspond to a reduction in water and water-related energy costs for those households by between 4% and 31%. Showers are therefore likely to offer a significant point of influence for WRE use within households.

Hot water system type moderates the impact of WRE use characteristics

Hot water system energy losses were identified as a key driver of differences in WRE use between the households studied in Chapter 4. In Chapter 5 it was further demonstrated that the interaction between the hot water system and end use behaviour is important. This is a result of the fact that for instantaneous type hot water systems, energy conversion efficiency losses scale with the volume of hot water used, in comparison to storage hot water systems for which losses are relatively fixed. It was shown that instantaneous type hot water systems are likely to be more efficient (i.e. lower energy losses) in households with a lower volume of hot water use (lower shower flow rates, duration or frequency, or lower household occupancy), whereas storage type systems will be more efficient in households with a higher volume of hot water use.

Limitations and insights for broader-scale analysis

The quantitative analysis presented in Chapters 4 and 5 represents a small selection of individual households. Focus of the work was on detailed description of household characteristics, and the contribution of these characteristics to variation in WRE use between individual households. The work was not intended to capture all representative household types. Outcomes of the work provide insight into research opportunities at a larger, more representative scale (e.g. city-scale), by (a) describing points of difference in WRE, costs and GHG emissions between seven individual households; (b) identifying which characteristics contribute most to these differences; and (c) highlighting the implications for integrated management of household water and energy use. Furthermore, in Chapter 4 it was highlighted that modelling results indicated significant variations in water and energy uses between households, and comparison of the sample to average Australian household water use demonstrated that the sample captures a broad cross-section of total water use characteristics. The research outcomes presented therefore provide a valid basis on which future research can be founded.

7.1.2. Hypothesis ii): There are pathways through which resource managers can influence water-related energy use in households

Consumer education and residential building standards as pathways of influence

Chapter 6 offered insight into medium-term policy opportunities to influence water-related energy use in households, in the perspective of key stakeholders in management of water, energy and residential buildings policy in urban Victoria. Key medium-term opportunities were highlighted in (a) consumer education and advocacy targeting user behaviour and technology choice, and (b) the further development of residential building standards to better manage selection and layout of building services.

Shower behaviour change and technology choice as a focus for WRE management

In Chapter 5, behaviour change focused on showering was demonstrated to have significant potential to reduce WRE use and associated costs for the households studied (as discussed in Section 7.1.1). Concurrent work published with Kenway et al. (2016) built on the analysis of the seven household presented in Chapter 4 of this thesis, and demonstrated that both behavioural and technical factors can play an important role in water-related energy management. The work demonstrated that shower duration, flow rate, frequency and temperature, in addition to hot water system efficiency, adult population, and the temperature of cold water, all had a significant influence on household WRE use. It also highlighted that shower duration and flow rate offer the most scope for change. These factors therefore offer scope for WRE demand management programs through a focus on consumer education and advocacy which target user behaviour and technology choice.

Focus of messaging matters for impacts of WRE education and advocacy

Research findings in Chapters 4 and 5 are instructive regarding messaging for consumer education and advocacy on WRE use. Notably, Chapter 4 highlighted that the content of information may vary according to the intended management impact of any demand management program. Different household end uses were shown to be influential for each management impact category: showering, energy loss from hot water systems, and clothes washer use were demonstrated as influential for household WRE use (kWh); showering, clothes washer and dishwasher use as influential for GHG emissions associated with WRE (kg CO_2-e); and showering and clothes washer use for water and related energy use costs ($). Chapter 5 further highlighted that an electric storage hot water system would consume less energy at the household (kWh) for water heating than a gas storage or instantaneous type system (due to lower energy conversion efficiency losses for electric storage systems), but would: (a) cost substantially more to run for the Melbourne households studied (due to higher cost per kilowatt-hour under electricity tariffs); (b) consume significantly more primary energy (3 kWh thermal energy required to generate 1 kWh of electric energy); and (c) would have higher associated GHG emissions (for contemporary Victorian electricity supply, at 1.17 kg CO_2e kWh^{-1}). It is noted that consumer tariffs, primary energy consumption and the GHG intensity of electricity supply are not fixed, and will change over time according to energy markets and the mix of generation technologies, and therefore the relative impacts of management interventions will shift accordingly. Consequently, prior to initiating any WRE-focused management intervention it will be important to first clearly identify both the desired and likely impacts, to ensure that the appropriate end uses are targeted to achieve intended outcomes.

A consistent focus on both water and energy use messaging will be important in demand management interventions. It was highlighted in Chapter 4 that the households studied with solar hot water systems showered more frequently and for significant duration when compared with other households studied, demonstrating higher per-capita and total water use. In contrast with significantly reduced need for purchased energy for water heating (50% to 67% reduction), this highlights potential impact of inconsistencies between water efficiency and energy efficiency messaging. While reducing operational GHG emissions for households, solar hot water use has the potential to lead to increased water consumption in response to a ‘solved’ hot water problem, if not accompanied by a focus on water use behaviours and fittings. Furthermore, given that water costs dominated variable utility costs for WRE end uses in the Melbourne households studied, energy cost savings through solar hot water use may be more than offset by increased water costs if water use is not also managed. This also suggests that water cost management may be a good focus for both water and associated WRE management in Melbourne households, particularly if showering is a focus (high water and WRE use). However, in Chapter 6 it was highlighted in stakeholder interviews that cost-focused messaging might only have short-term benefits for household consumers, leading to longer-term market backlash.

Stakeholder views in Chapter 6 highlighted potential messaging avenues for WRE-focused behaviour change. These included the incorporation of energy information into residential water bills to highlight the likely energy impacts of water use. The growth in opportunities presented by smart metering and ‘internet of things’ technologies for water-energy impact communication and management was also highlighted as a promising pathway which could be leveraged for household WRE management.

Hot water systems as a focus of residential building standards for WRE management

Standards regulating the selection and layout of building services emerged as an important gap identified through key stakeholder interviews in Chapter 6. Stakeholders noted that although the building design stage is where most opportunity exists to influence operational water-energy impacts, there is currently a big gap in water-energy considerations at this stage. Hot water systems are likely to present an important target for residential building standards. Chapter 4 identified the important contribution of HWS efficiency losses to differences in total WRE between households. In Chapter 5 it was further highlighted that the selection of efficient hot water systems for households should consider characteristics of the household and anticipated water use patterns. This is in consequence of the fact that gas continuous type hot water systems were found to be more efficient (i.e. lower energy losses per person) in households with lower-volume hot water use, and gas storage systems to be more efficient in households with higher-volume hot water use (as discussed in section 7.1.1 above). It is therefore likely that gas continuous systems are most beneficial in small households, or households with significant fluctuation in occupancy, as energy use (and losses) for hot water heating scale with volume of use in these systems. Gas storage systems are likely to be better suited to large households with more stable occupancy, as greater volumes of hot water use reduce the proportional storage energy losses per person – however selection of appropriate storage size will become important in these cases.

Stakeholder views in Chapter 6 also highlighted that the further development of residential building standards to consider operational water-energy impacts (such as hot water system selection) would assist in overcoming a key barrier to end-use WRE management, in the form of mixed incentives for residential builders/developers (who select and install systems, but bear no cost for ongoing operational impacts) and residents/tenants (who typically have no impact on selection and layout, but do bear the costs for ongoing operational impacts).

7.1.3. Hypothesis iii) There is sufficient motivation / capacity for resource managers to engage in integrated water and energy management

Consumer impacts as common motivator for engaging in WRE management

Consumer impacts are a common issue of interest to all stakeholders interviewed, and may have the potential to motivate stakeholders across diverse fields to engage in WRE management. According to the principles of transitions management, if integrated management of household water and energy use is to be achieved, a common goal or vision will be important to motivate the work of the diverse actors involved towards an integrated WRE management focus. Research outcomes presented in Chapter 6 showed that the objectives of key actors who have an interest in influencing household water and/or energy management vary across sectors. These interests vary from environmental protection, emissions reduction, resource efficiency, security of supply and affordability of essential services. However, despite this variation, affordability of essential services was found to be a common concern across all stakeholders interviewed. A focus on consumer impacts is therefore a common issue of interest with the potential to achieve buy-in from stakeholders across diverse fields. Opportunities to achieve this include a focus on cost of water and/or energy services (i.e. through tariffs, or management of volumetric usage), or through a focus on consumer amenity (i.e. thermal comfort, water/energy productivity). It was noted that a focus on household bill reduction by managing consumer usage volumes has the potential to lead to negative consumer outcomes in the longer term, as it would likely to lead to backlash through market pricing mechanisms as water and/or energy suppliers seek to cover their costs. The disadvantages associated with such cost-focused approaches should be considered before adoption as a WRE management measure.

State government as a key actor in enabling and/or implementing new policy

State government policy and/or priority changes were the most frequently referenced context that had facilitated stakeholders' past experiences of policy innovation, in work presented in Chapter 6. The importance of the state government role was echoed in stakeholder views of potential opportunities in WRE management, with multiple respondents of the view that any shift towards greater integration in water and energy use management would need to be driven by state government. Several reasons were given for this, including: (a) the fact that state government is best placed to have a holistic view of cross-cutting issues across water-energy siloes, particularly with water and energy issues falling under the same department in Victoria; (b) that state government would have the most interest in seeing solutions to cross-cutting issues (such as WRE) and consequently in creating an environment to implement those solutions; and (c) that state government has the authority to develop policies and set direction to create such an environment.

Authority, legitimacy, and social capital as policy innovation resources

New policy development for water-related energy management may be most effectively driven by actors who either (a) have the authority to set direction in water / energy / residential construction regulation and management; (b) for whom creation of WRE-focused policy can be demonstrated to reflect the expectations of the greater community; and/or (c) who have strong networks of relationships with industry and community. Authority (i.e. the legitimately recognised right to make decisions) was found to be an important resource which can underpin the capacity to create new policy, particularly in the past experience of government and water and energy utility stakeholders interviewed in

Chapter 6. These actors provided past examples of new policy direction setting in areas in which they were formally recognised as having the power to make such decisions (i.e. water network management, local government planning regulation, energy network management, and water security planning). For other stakeholders, including NGOs, local council and state government actors, legitimacy (i.e. actions congruent with expectations of the greater environment) was an important resource supporting policy change. This was noted in the form of policy action congruent with recognised community expectations (expressed through council), and through consultation with industry networks supported by transparent and accountable decision making. Similarly, multiple stakeholders interviewed provided examples of leveraging strong industry and community relationships to understand and address concerns, building on trust through transparent processes, and to share information to support new policy.

Flows of information as innovation strategies

Research presented in Chapter 6 found that strategies which had been successfully employed in past policy innovation focused primarily on flows of information, including cost-benefit analysis (economic and non-economic cost), identification of emerging sectoral trends, and advocacy and networking to garner support. Consequently, future work focused on development of data collections to support cost-benefit analysis of the expected impacts of household WRE management policy, in both economic and non-economic (e.g. health and wellbeing) terms, is likely to support policy innovation for improved WRE management.

Information complexity and fragmented cost-benefit impacts present challenges for achieving WRE management

In Chapter 6, it was highlighted that to achieve WRE management, it will be important to address existing barriers in the form of complex information needs and skill requirements, and fragmented responsibilities, costs and benefits. Interaction between these issues was highlighted, with fragmentation of water-energy responsibilities noted as a barrier to collecting the complex data required to account for water-energy interaction (due to an inability to justify increased expenditure on issues beyond the core focus of a water / energy / supply / use focused role). The development of benefits-sharing frameworks, and support for inter-organisational collaboration, may have the potential to contribute significantly in this context.

7.2. Recommendations for future work

The following recommendations are made with regard to improving understanding of household water-energy interactions:

- Extension of quantification of household water-energy use linkages to consider:
  - dynamic daily and/or seasonal analysis, in particular consideration of time-of-use impacts and flow-on effects to water, electricity and gas networks (e.g. peak demands).
  - larger sample size with diverse demographic characteristics, including a strong focus on detailed understanding of configurations for hot water systems, showers, clothes washers and dishwashers.
- Development of water-energy end use models which can account for impacts of end use on consumer welfare impacts (e.g. comfort, wellbeing).
- Further investigation to confirm hot water system efficiency loss characteristics, particularly gas instantaneous systems.
- Further analysis of impacts of selection and layout of household of water and energy services on water-related energy use, to inform residential building standards.
- Analysis of the likely WRE impacts of increases in gas tariffs, trends in household energy connections (gas or electricity), and impacts of GHG intensity of supplies (gas vs. fossil-fuel based electricity vs. renewables-based electricity grid).

The following recommendations are made with regard to advancing policy for improved WRE management:

- Policy framing and data focused on impacts of WRE use on household cost of living, as a unifying vision across key stakeholders and sectors;
- Advocacy to shift state government policy priorities to a clearer focus on integration of water and energy management considerations, or anticipation of emerging government priorities and the pre-emptive demonstration of the relevance of WRE management to those priorities;
- Development of information to support cost-benefit analysis of the expected impacts of household WRE management policy, in both economic and non-economic (e.g. health and wellbeing) terms;

- Development of information to support selection and layout of water and energy services in residential buildings for improved WRE outcomes;
- Development of tools and materials to improve literacy in, and visibility of, household water-energy interactions;
- Development of 'shared value' frameworks to better distribute the costs and benefits of WRE management.

A summary of key policy recommendations against the systems interventions framework (introduced in Chapter 2) is presented in Table 23. According to the systems intervention framework, actions presented towards the bottom of the table are achievable in the shorter-term and have a modest scale of impact, whereas actions higher in the table increase in both scale of effectiveness and the time and effort required for implementation.

Table 23: Summary of key policy recommendations against system intervention framework

Intervention point	Policy recommendation
Goals of the system	• Policy framing and data - focus on household cost of living impacts of water-related energy use, as a unifying vision to drive policy innovation.
Rules of the system	• Development of 'shared value' frameworks to better distribute costs / benefits of WRE management. • Further development of residential building standards to account for water-energy interaction in layout of building services.
Structure of information flows	• Development of methods to support accounting of impacts of water-related energy management in economic and non-economic (e.g. health and wellbeing) terms. • Creation of tools and materials to improve literacy and visibility of household water-energy interactions.
Constants / parameters	• Investigation to confirm hot water system efficiency loss characteristics, and incentives to improve.

7.3. Summary comment

This thesis has successfully addressed the following research objectives:

1) *Quantifying WRE use in individual households, and identifying household characteristics which contribute significantly to variation.*

   Analysis of seven individual Australian households (five in Melbourne, Victoria, and two in Brisbane, Queensland) found that WRE use ranged from 7 to 21 kWh hh^{-1} d^{-1}, representing 13% - 24% of total household energy use in the Melbourne households and 76% - 79% in the Brisbane households. Detailed end-use analysis of the Melbourne households showed that shower use (11% – 61% of WRE), hot water system energy losses (8% - 31% of WRE) and clothes washer usage (4% - 17% of WRE) contributed most to variation in WRE use between households.

2) *Quantifying impacts of a water demand management scenario, and identifying influential factors leading to differences in impacts between households.*

   Shower duration management (through simulation of a hypothetical scenario) was found to reduce energy demand for all households studied. By reducing shower duration to four minutes per shower (from baseline durations of between six to ten minutes), the reduction in energy demand across the five households studied was between 0.1 and 3.8 kWh p^{-1} d^{-1} (or 9% - 63% of baseline WRE use). For gas powered hot water systems, continuous type systems were found to be more energy efficient in lower flow shower (4.4 – 6 L min-1) households, whereas storage type systems were found to be more energy efficiency in households with higher flow showers (9 – 10 L min^{-1}). In response to the hypothetical shower demand management scenario, savings in combined water and energy cost across the five households studied were \$37 to \$500 hh^{-1} y^{-1} (4% - 31% reduction from baseline). Cost savings would be more significant for scenarios in which electric storage systems are installed.

3) *Exploring the potential for policy and regulation for household WRE management in urban Victoria.*

   Stakeholder objectives regarding residential water and/or energy management varied across sectors, but cost of living was a common theme which may offer a basis for a shared vision for transition towards improved household WRE management. State government policy and/or priority changes were the most common context referenced as underpinning stakeholders' past experiences of policy innovation. Strategies which had been successfully employed in policy innovation focused primarily on flows of information, including cost-benefit analysis (both economic and non-economic cost), the identification of emerging sectoral trends, and advocacy and networking to garner support. Key medium-term opportunities for household WRE management were noted in consumer education and advocacy around water-energy impacts, and the development of residential building standards to better manage selection and layout of building services. These opportunities are tempered by noted barriers in the form of complex information needs and skills required to understand water-energy impacts (for industry and consumers alike), and fragmented cost-benefit arrangements between (a) supply versus use, (b) distribution of services versus retail supply, and (c) residential developers versus residents.

In addressing these research objectives, two research papers have been accepted for peer-reviewed publication in a high impact journal (Journal of Cleaner Production, 2016 impact factor 5.715). Combined with podium presentations at both international and national conferences (World Water Congress Brisbane 2017, and Ozwater Brisbane 2016), the research outputs of this PhD thesis have achieved substantial recognition.

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Appendix A – Ethics approval 2012001201

THE UNIVERSITY OF QUEENSLAND

Institutional Human Research Ethics Approval

Project Title:	Water-Energy-Carbon Links In Households And Cities: A New Paradigm
Chief Investigator:	Dr Steven Kenway
Supervisor:	None
Co-Investigator(s):	Prof Paul Lant, Prof Brian Head, Amanda Binks
School(s):	Department of Chemical Engineering
Approval Number:	2012001201
Granting Agency/Degree:	Smart Water Fund; ARC Linkage Project
Duration:	31st December 2015

Comments:

Expedited Review - low risk.

Note: if this approval is for amendments to an already approved protocol for which a UQ Clinical Trials Protection/Insurance Form was originally submitted, then the researchers must directly notify the UQ Insurance Office of any changes to that Form and Participant Information Sheets & Consent Forms as a result of the amendments, before action.

Name of responsible Committee:
Behavioural & Social Sciences Ethical Review Committee
This project complies with the provisions contained in the *National Statement on Ethical Conduct in Human Research* and complies with the regulations governing experimentation on humans.

Name of Ethics Committee representative:
Associate Professor John McLean
Chairperson
Behavioural & Social Sciences Ethical Review Committee

Signature ____________ Date 1/11/2012

Appendix B – Ethics approval 2017000659

THE UNIVERSITY OF QUEENSLAND

Sub-Committee Human Research Ethics Approval

Project Title:	Assessing capacity and motivation for residential water-related energy management in urban Victoria
Chief Investigator:	Miss Amanda Binks
Supervisor:	A/Prof Steven Kenway Prof Paul Lant Prof Brian Head
Co-Investigator(s):	None
School(s):	EAIT
Approval Number:	2017000659
Granting Agency/Degree:	None
Duration:	30th November 2017

Comments/Conditions:

- Application, 15/05/2017
- Participant Information Sheet, 30/05/2017
- Consent Form 30/05/2017
- Letter of Authority and Recognition, 15/05/2017

Note: if this approval is for amendments to an already approved protocol for which a UQ Clinical Trials Protection/Insurance Form was originally submitted, then the researchers must directly notify the UQ Insurance Office of any changes to that Form and Participant Information Sheets & Consent Forms as a result of the amendments, before action.

Name of responsible Sub-Committee:
University of Queensland Engineering, Architecture and Information Technology, Low & Negligible Risk Ethics Sub-Committee
This project complies with the provisions contained in the *National Statement on Ethical Conduct in Human Research* and complies with the regulations governing experimentation on humans.

Name of Ethics Sub-Committee representative:
Dr Timothy Nicholson
Chairperson
University of Queensland Engineering, Architecture and Information Technology, Low & Negligible Risk Ethics Sub-Committee

Signature ____________________ Date 30/05/2017

Appendix C – Semi-structured interview format

The following information sheet (see pages 148 - 149) was provided to interview participants, outlining:

- the interview process,
- the intended use of interview data, and
- contact details for the project investigator.

Interviews were conducted as an open conversation with the participant. After participants were presented with outcomes of the research presented in Chapters 4 and 5 of this thesis, the questions outlined in this information sheet were used to guide the interview process towards topics of interest. These questions were adapted to suit each participant, and questions were included or excluded as appropriate to the participant's role.

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Participant Information Sheet

- Interview Process

Exploring capacity and motivation for household water-related energy management in Victoria

Interview process and use of data

- Semi-structured interviews, approximately 1 hour duration.
- Interviews will be audio recorded for transcription purposes.
- All information will be de-identified and kept on a secure server by the researcher.
- Interviewees and their organisations will not be identified in any published analysis of the material.

Interview questions

As the interview will follow a semi-structured format, the interview will follow the thread of discussion and ask for elaboration on particular points of interest. Therefore, it is not possible to provide an exact list of the interview questions to be asked. However, the intention of the interview is to follow the subject areas listed below.

The following questions are indicative of the subject areas to be discussed during the interview (note: not all questions will apply to each person being interviewed):

Part A - your role:

- Can you give me a brief overview of the role of your organisation?
- Can you describe your role for me, and where it fits within the activities of your organisation? Team structure? Professional backgrounds and skills?
- Is your work usually project-based, or based on managing well-defined ongoing responsibilities? Or both, other?
- How are your work priorities set? Is there a strategic planning process that influences priority-setting, and if so can you describe it? (e.g. Who is involved, and what are key influences in the process? What is your involvement in this process, if any?)
- In what ways (if any) are the progress / outputs of your work tracked and/or measured?
- Can you describe the key relationships between your role and others **within** your organisation? How do these relationships influence the focus of your work?
- Can you describe the key relationships between your role/organisation and other **external** organisations? How do these relationships influence the focus of your work?
- Can you give me any examples of a new initiative (or policy or work priority) that you have seen impacting your area of work?

Interview questions (cont'd)

Part B - perspectives on water-related energy use and management:

- Can you briefly describe what you see as the current key influences on household water-related energy use and management in Victoria (focusing on showering and hot water systems)?
- Do you think that the issues of household water-related energy use currently have any relevance to your role, or to your broader organisation? If so, can you explain where you see the relevance?
- If household water-related energy use were to be considered as more important in the work of your organisation, how would it need to be measured / what information would be needed? (E.g. more detailed household water/energy meter data, reliable algorithms to estimate water/energy use changes in response to policy/program changes, etc.)
- Do you see any potential for increased integration and/or collaboration between household water and energy/GHG management in Victoria?
    - Are there any changes in the way it is currently managed that you think would help to facilitate this?
    - What challenges do you see for achieving this?
- What do you see as the most likely scenario for household water-related energy management over the next decade? (E.g. considering the current rate of changes in technology)
- If you were to describe your 'perfect world' vision of household water-related energy management in the future, what would that look like?

Project investigator contact details

If you have any questions or concerns regarding the interview process, please do not hesitate to contact me by phone or email, as listed below.

Ms Amanda Binks
Water-Energy-Carbon Research Group, School of Chemical Engineering
The University of Queensland, Brisbane, Australia
Email: a.binks@uq.edu.au, Telephone: <redacted>

Disclosure: This information is being collected solely for the purpose of completing a PhD research project under conditions of confidentiality and research integrity. The project investigator is currently employed part-time as an engineer with the Queensland Bulk Water Supply Authority (Seqwater).